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Bone-conducted tones masked by air-conducted noise

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BONE-CONDUCTED TONES MASKED BY AIR-CONDUCTED NOISE

by

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CHAPTER I

INTRODUCTION

When the head of a normally hearing listener is vibrated by a bone-conduction transducer, both ears are stimulated to approximately the same extent because acoustic energy is transmitted through the whole skull.[2,4] But bone-conduction audiometry is concerned primarily with the auditory acuity of one ear rather than both ears.

In order to determine the auditory acuity of one ear to bone-conducted tones or signals, a common audiometric procedure is to mask the bone-conducted signal stimulating the other ear by means of air-conducted noise. However, there are no quantitative data on exactly how air-conducted noise does, in fact, mask a signal that is introduced to a single ear by bone conduction.

The primary purpose of this study was to develop and evaluate a method for obtaining monaural thresholds for bone-conducted signals masked by air-conducted noises. The development of such a method would be simple if persons with one 'normal' ear, one 'dead' ear, and a normal skull could be obtained; that is, certified unilateral listeners. However, such listeners are not readily available.

Therefore, since the two ears of normal listeners are stimulated nearly identically by bone conduction, a method for determining thresholds for bone-conducted signals masked by air-conducted noise at one ear requires the functional elimination of the other ear. The elimination of the other ear can also be accomplished by means of air-conducted noise. Masked thresholds can then be determined at one ear provided that the noise at the other ear is maintained at a sufficiently high level to eliminate the effects of the signal at that ear.

In order to clearly identify the two air-conducted noises, the noise at the ear for which threeholds are to be determined will be called 'masking noise', while the noise at the ear to be eliminated will be called 'blocking noise'.

The results from such a method might allow one to calculate for a given air- and bone-conduction transducer configuration the amount of air-conducted noise required to produce a specific amount of masking for the bone-conducted signal in a single ear.

The results might also be used to test the hypothesis that the same one-to-one correspondence between changes in level of the masking noise and the signal threshold obtain as for the familiar experiment of signals masked by noise when both are heard by air conduction[19].

If data on physical measures of both air-and bone-conduction stimulation that produce equivalent effects on the inner ear could be obtained by use of the method, such data might be useful to other investigators who are trying empirically and theoretically to compare hearing by air and bone conduction. The method could provide such data at the high signal levels required for masked thresholds as well as the low signal levels required at quiet threshold.

Finally, the method might be useful as an adjunct to the 'real head' calibration procedure for bone-conduction transducers presently in use. In particular, it would eliminate the requirement for low ambient noise in the testing room; possibly provide less variability in thresholds than obtained for quiet thresholds (similar to results reported for conventional masked thresholds relative to quiet thresholds for air conduction); and provide calibration levels well above the normal quiet threshold, thus resulting in a psychophysical measure of the linearity of bone-conduction transducers as a function of input level.

A search of the literature provided no direct information on such a method for obtaining thresholds at one ear for bone-conducted tones masked by air-conducted noise. However, certain information from investigations of hearing by bone conduction is relevant to both the development of the method and possible applications of it, and this information is reviewed below.

Past Investigations

Stimulation of the inner ear was found to be identical for both air-and bone-conduction pathways first by Bekesy[4] and later by

Barany[2] in psychophysical experiments, and subsequently this fact was supported by Lowy[25] and Wever and Lawrence[33] in psysiological experiments.

With this fact well established, many investigators[2, 4, 5, 6, 9, 11, 15, 16, 17, 26] turned to the problem of defining and measuring the physical characteristics of the bone-conduction pathway. Some of the results from these investigations encouraged others[7, 8, 20] to attempt the development of physical devices for use as a standard for the calibration of bone-conduction transducers. Although early attempts to build such devices were not successful, a recent effort[31] seems to have produced a device that not only simulates most of the known properties of the head[9] but also may provide a stable and accurate method for the calibration of bone-conduction transducers. This device or 'artificial mastoid' may replace the so-called 'real-head' method of calibration that has been in general use.

The real-head method equates a voltage across the transducer (physical measure) to the threshold (psychophysical measure) produced by the vibratory energy imparted to the head by the transducer. Such a calibration procedure may be confounded by several factors which may not always be controlled. These factors may increase the variability in threshold measurements and, thereby, reduce the accuracy of the calibration procedure to an approximation rather than a primary calibration method.

Many of these factors have been investigated, although not always in a quantitative manner, and indicate that auditory stimulation by bone conduction when compared to air conduction is a very complex phenomenon. Those factors which bear directly on the real-head calibration method and that are relevent to the present study are:

Position. Barany[2] and other investigators[4,18,21,22,23,27,29] have reported that the frontal bone site has a distinct advantage over other positions, such as the frequently used mastoid position, because the intra-subject variability among thresholds is lower at the frontal position than it is at the other locations on the skull. The mastoid position, on the other hand, is unacceptable due to its near approximation with the cartilagenous external meatus with the result that sound pressure variations are produced therein which, in turn, undoubtedly cause stimulation of the ear by air conduction.[2,18,29]

Coupling Force. It has been widely accepted on a quantitative basis that regardless of the position of the transducer on the skull, the stability and sensitivity of thresholds below 1000 cps seem to be affected by coupling force. König[23] and Hoops and Curry[21] quantitatively investigated the relation between threshold and coupling force and concluded that a force less than 500 grams results in unstable and progressively poorer thresholds as the test frequency is decreased below 1000 cps. Above 1000 cps thresholds seem to be little affected by changes in force. Their results indicate that a coupling force between 500 and 1000 grams will minimize both the threshold levels and their variability.

Present Investigation

In the development of the method for obtaining monaural thresholds for bone-conducted signals masked by air-conducted noises, two factors concerning the relations between the air-conducted noises and the bone-conducted signals must be considered. One factor is the difference in level between the blocking and masking noises required such that the blocking noise is of sufficient level to functionally eliminate or 'block' the signal from the unwanted ear. The other is the possible effects of the blocking and masking noises on the bone-conducted signals.

The factors described above were investigated by Weston and Miller,[32] but only for the case of signals presented by air conduction. The conditions used in their experiment are analogous to those under consideration in this study since the only difference was the signal pathway. Weston and Miller presented binaural signals by air conduction that were known to be identical in all respects at the two ears. In the present study the signal is presented by bone conduction and it is assumed to stimulate the two ears identically in all respects. Therefore, the results obtained by Weston and Miller appear to be relevant to the two factors under consideration. The results of their experiment strongly suggest that one ear can be effectively eliminated from a monaural masking experiment by a blocking noise that is about 25 dB higher in level than the masking noise and that binaural interactions between the signals and the noises do not occur provided the noises are statistically independent of one another.

Previous literature and the results of Weston and Miller suggest for the case of bone-conducted signals that monaural masked thresholds could be determined provided the blocking noise is at least 25 dB higher in level than the masking noise. Signals introduced by bone conduction are about equal in level at the ears of normally hearing listeners. When such a listener adjusts the signal to threshold in the ear receiving the masking noise, then the signal in the unwanted ear would be about 25 dB below its own monaural threshold. This, of course, would be true since the blocking noise in the unwanted ear is 25 dB higher than the masking noise. Since several lines of evidence support the notion that a tone which is 25 dB below its monaural threshold has almost no effect on the auditory system, it seems safe to assume that the signal in the unwanted ear has been effectively removed from the experiment.

It can also be reasoned that the blocking and masking noises must be independent of each other; that is, derived from independent noise generators. The reason for this requirement can be understood if one considers the case where the blocking and masking noises are from the same noise generator. In this case, the noises at the two ears would be identical in all respects but amplitude. Now, if the level of the blocking noise be 25 dB greater than that of the masking noise, the signal would be effectively blocked from one ear; but the noise would, nonetheless, by itself, influence the masked threshold in the opposite ear. Indeed, the results of Weston and Miller, show such effects. If, however, the noise used as a blocking noise is statistically independent of the masking noise, little or no effect of the blocking noise is observed on the masked threshold in the opposite ear.

The three experiments to be reported here investigate the adequacy and usefulness of the method for measuring the masking of bone-conducted signals by air-conducted masking noise at one ear and air-conducted blocking noise at the other ear at which the effects of the bone-conducted signals are to be eliminated.

Experiment I shows that for bone-conducted signals, as was the case for air conduction (Weston and Miller), the blocking noise must be both independent of and about 25 dB greater than the masking noise. This experiment comprised two major variables: one, the difference in level between the blocking and masking noises, and the other, the correlation between them (that is, the noises had either a positive correlation of plus one or they were statistically independent (uncorrelated)).

Experiment II was conducted to test the hypothesis that the masked thresholds for air conduction are identical for the following three conditions: (1) the usual monaural masked threshold with both signal and noise delivered to the same ear; (2) same as (1) but an independent noise added to the opposite ear at a level 25 dB greater than the masking noise; and (3) same as (2) but with an additional signal, identical in all respects to the original one, introduced into the opposite ear. Since the hypothesis was confirmed by the experiment, the air-conduction thresholds that were to be used for comparison with the bone-conduction thresholds in Experiment III had only to be the usual monaural ones, i.e. condition (1).

In Experiment III, extensive use of the method for measuring the masking of bone-conducted signals by air-conducted noises in a single ear would test the accuracy of the method, and perhaps, reveal some of its deficiencies or, at least, indicate relevant factors that had not yet been anticipated.

However, since there were no reasons other than its novelty to doubt the method, Experiment III was also designed:

(1) to test the hypothesis that the shapes of the curves relating monaural masked threshold to noise level are identical for both air- and bone-conducted signals.

(2) to determine, for a given air- and bone-conduction transducer configuration, the amount of noise required to produce a specific amount of masking of a bone-conducted signal at an ear.

(3) to provide for the calibration in physical units of both the air- and bone-conduction transducers. (Thus, physical measures could be calculated for both air- and bone-conducted signals when they are set to threshold intensity).

(4) to obtain psychophysical measures of the linearity of the bone-conduction transducer as a function of input.

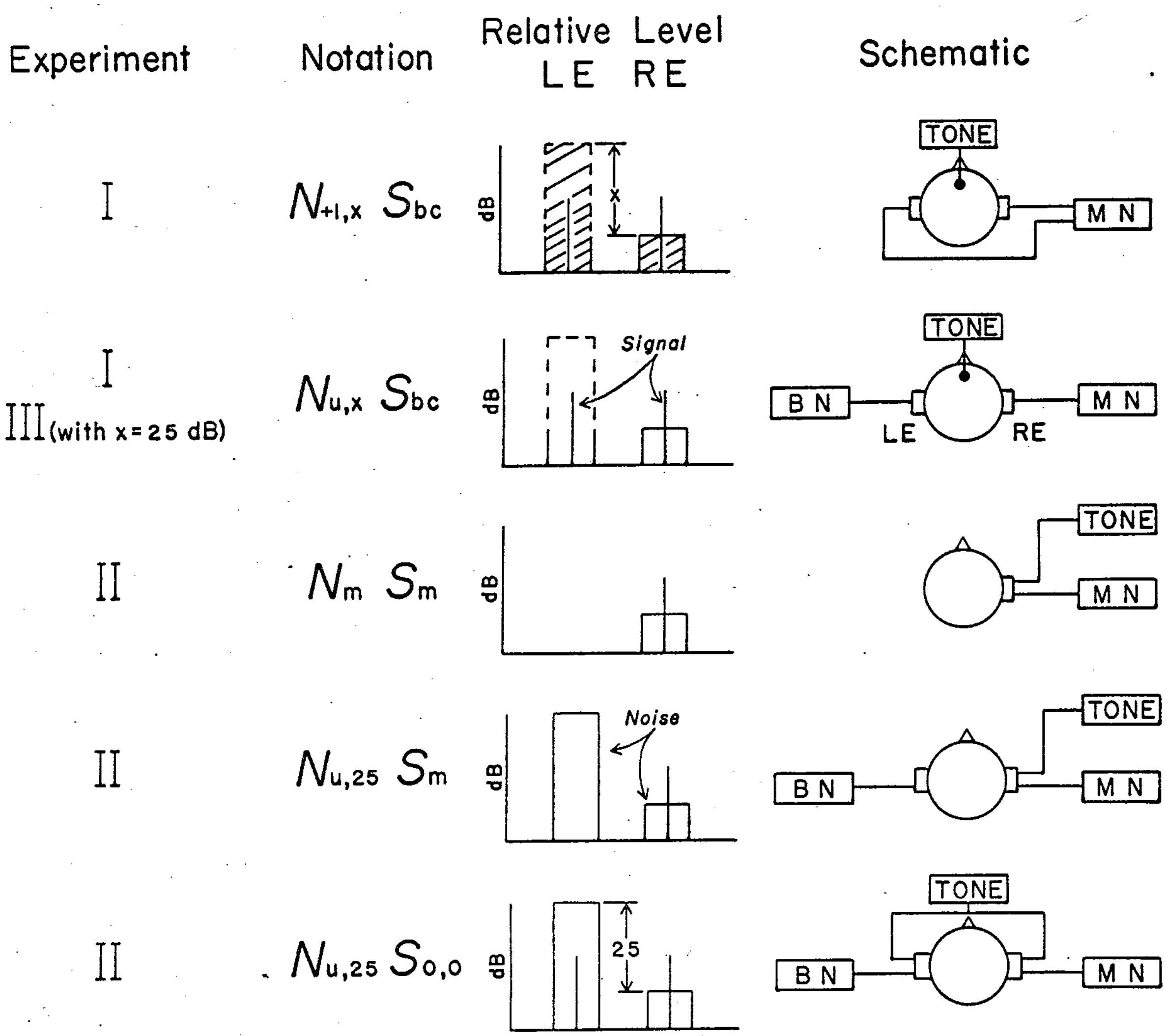
(5) to assess the 'occlusion effect' on the masked as well as the quiet threshold of bone-conducted signals. (Bone-conduction thresholds at low frequencies are lowered by occluding the ears. Therefore, since the method required earphones, Experiment III included two kinds of earphones, one, in common use in experimental and clinical work, that produces a sizable occlusion effect by virtue of a small enclosed volume, and the other, although not widely available, with a large enclosed volume, that produces little or no occlusion effect).

(6) to obtain measures of the variability of thresholds obtained by bone conduction in the quiet and in masking noise.

Since in the experiments to be reported there are several complicated combinations of signals and noises at the two ears, it is necessary to describe these conditions and present a notation which will provide a short-hand description of them. The notation and corresponding description are given below and the same notation illustrated by diagrams is given in Fig. 1.

The notation, although somewhat different from that used by others for the description of tonal signals and noises at the ears, allows for the expression of the difference in levels at the two ears. The first subscript indicates the correlation or phase between the noises or signals at the two ears if both ears are stimulated. A plus one stands for a positive and perfect correlation, while a <u>u</u> stands for uncorrelated or statistically independent noises. A zero indicates that the signals are in phase. If the first subscript is the letter <u>m</u> , the experiment was monaural. The letters <u>bc</u> indicate that the tonal signal is presented by bone conduction. An <u>x</u> for a second subscript means that the difference in levels between the ears is a variable; if this second subscript is a number, the number is the level of the blocking noise minus the level of the masking noise in decibels. The diagramatic illustrations show the blocking noise (BN) at the left ear and the masking noise (MN) at the right.

The conditions shown in Fig. 1 are as follows.



Notation Legend

N-Noise
S-Tone
m-Monaural
u-Independent (2) noise sources

+I-Identical (I) noise source
o-In phase (2) signals
o-Signals (2) equal level
bc-Bone-conducted tone

MN-Masking Noise
BN-Blocking Noise
25 -(BN-MN)=25 dB
x -(BN-MN)=x dB

Fig. 1. Notation for the experimental conditions illustrated by diagrams. The conditions used in each of the three Experiments are also shown.

(1) $N_{+1, x} S_{bc}$. The noises are identical at the two ears in all respects except amplitude and x is the level of the blocking noise (BN) minus the level of the masking noise (MN) in decibels, or (BN-MN)=x dB. The signal is presented by bone conduction.

(2) $N_{u, x} S_{bc}$. This condition is the same as (1) above but the noises at the two ears are independent.

(3) $N_m S_m$. Signal and noise are presented to the right ear by air conduction.

(4) $N_{u, 25} S_m$. The noises are independent at the two ears and (BN-MN)=+25 dB. The signal is presented to the right ear by air conduction.

(5) $N_{u, 25} S_{o, o}$. This condition is the same as (4) above but the signals are in phase and of equal amplitude at the two ears.

Chapter II

APPARATUS and GENERAL PROCEDURE

Apparatus.

The apparatus used in these experiments will be described under five headings. First, the overall properties of the channels used for noises and tone will be described and then the transducers and the apparatus used for their control and calibration will be described in detail.

Noise and Tone Channels. Figure 2 is a block diagram that shows the essential features of the noise and tone channels used in these experiments. Basically, there are three channels for generating tones and noises: one for the right earphone, one for the left earphone, and one for the bone-conduction transducer. These channels will be called the right channel, the left channel, and bone channel, respectively.

Consider now the right and left channels. In each of these channels the output of a noise generator (CID No. 24 or Grason-Stadler, Model No. 455B) was led to a low-pass filter (Spencer-Kennedy Labs., Model No. 302). The low-pass filters had a rejection rate of 18 dB per octave above the cut-off frequencies which were set to either 700 or 7000 cps. The output of the filter in each channel was then amplified (Langevin, Model L17A in the right channel and General Radio, Type 1206-B in the left). The amplifier outputs could be switched by switch No. 1 so that the initial portion of the left channel was disconnected and the output of the amplifier in the right channel was led into the remainder of both the left and right channels. In another position of switch No. 1, the right and left channels remained isolated; each being connected to its own noise generator, filter, and amplifier combination. Two remaining positions of switch No. 1 allowed noise to be introduced into only one of the two channels, either the right or left. The levels at the outputs of the switch were maintained constant, independent of the switch position, by means of fixed-loss pads within the switch circuitry. The vertical and horizontal inputs of an oscilloscope (Heathkit, Model LO-10) were bridged across the outputs of Switch No. 1 in order to provide a visual monitor of both noise channels and their correlation.

Each output of switch No. 1 was fed to a set of precision decade attenuators (Langevin, Models AT-505 and AT-510) and each set had a maximum attenuation of 110 dB. These attenuators were variable in 1-dB steps. The output of the attenuator set in each channel fed a three-way resistive mixing network. The output of each mixer was fed in turn to an impedance matching transformer (UTC, Model CVL-1). The transformers were

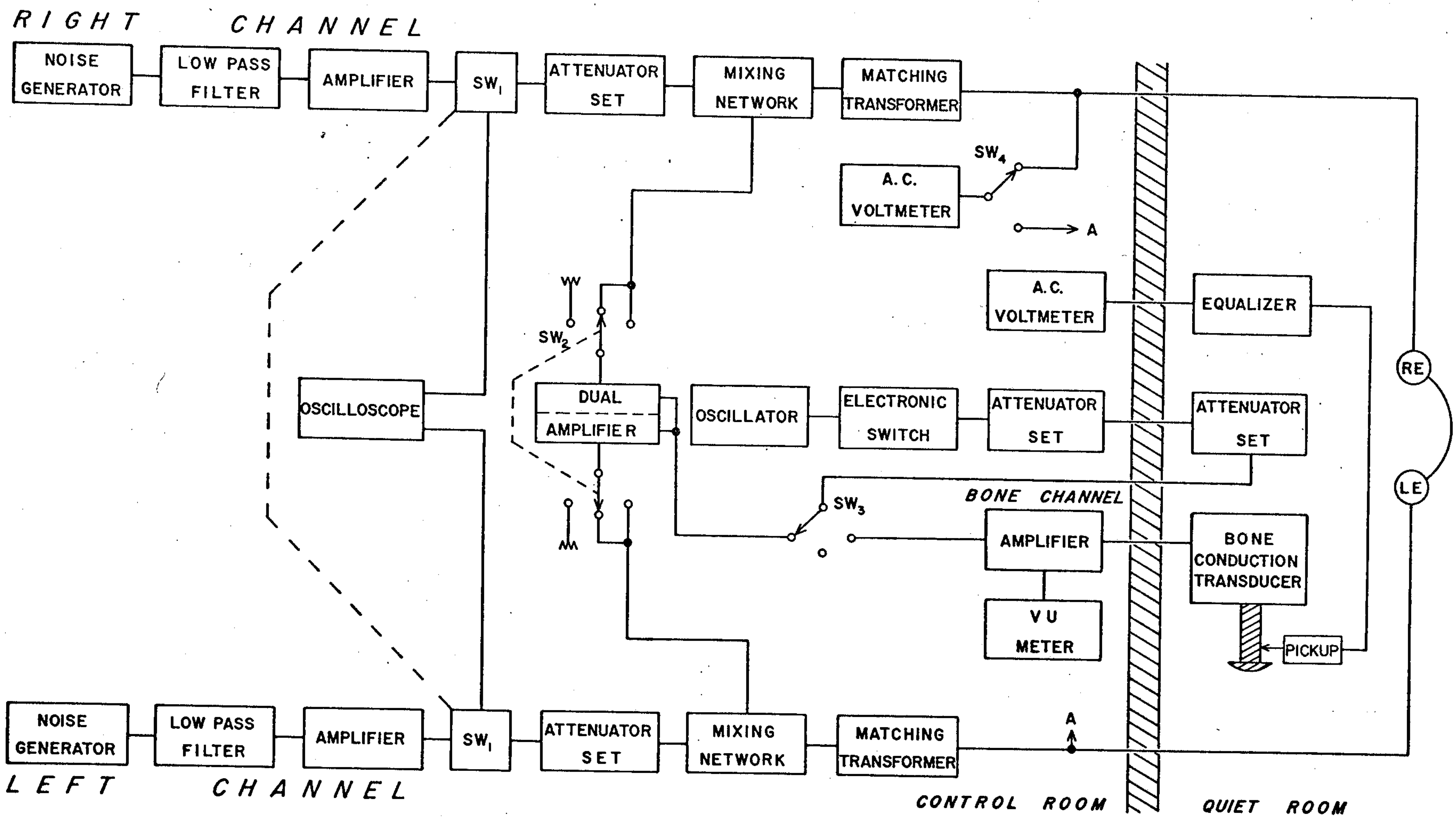


Fig. 2. Block diagram of the electronic apparatus.

strapped for an input impedance of 600 ohms and an output impedance of 10 ohms.

A two position switch (SW_4) was bridged across the outputs of the transformers and connected to an AC voltmeter (Ballantine, Model 300) for voltage calibrations of each channel. Cables connceted the outputs of the transformers to a terminal board in the quiet room for connection to the earphones.

Pure tones could be generated and mixed into the right, left, or bone channels by the following series of devices. The output of a pure-tone oscillator (Hewlett-Packard, Model 241A) was fed to an electronic switch (CID No. 53), triggered by means of a square wave generator (CID No. 53), so that a pulsed tone (on-off ratio, 50%; period, 500 msec; and rise-fall time, 20 msec) was available as a signal. This signal was fed to two precision attenuators in tandem, The first was an attenuator set (Langevin, Models AT-505 and AT-510) with a maximum attenuation of 110 dB and steps of 1 dB and this attenuator was controlled by the experimenter. The second attenuator (Daven, Model Spec. 4388G) had a maximum attenuation of 45 dB with 1-dB steps; it was under the control of the subject and located in the quiet room. A 10-dB pad could be inserted at the output of this attenuator by means of a switch located in the same box as the attenuator.

The output of the subject's attenuator was connected to a three position switch, switch No. 3 (SW_3). By means of this switch the pulsed tone could be introduced into the bone channel, or, for measurements of thresholds by air conduction, was connected to the inputs of two identical line amplifiers (CID No. 141) whose outputs each fed one of the three-way mixing networks in the right and left channels. The line amplifiers were used to provide better than 80 dB isolation between the two channels. Switch No. 2 (SW_2) allowed the pulsed tone to be fed to either the right or the left channels or to both channels simultaneously.

When switch No. 3 was set so that the pulsed tone was to be fed into the bone channel, the circuit was as follows. The output of the subject's attenuator was fed to a fixed attenuator (not shown) and then to a power amplifier (McIntosh, Model 50W-2), whose output was terminated at the bone conduction transducer. A VU meter (Daven, Model 910-E) was bridged across the output of the power amplifier for voltage calibrations.

In order to facilitate both the rapid and accurate reading of the subject's and experimenter's attenuators, these attenuators were modified, by the addition of rotary switches, so that their settings were visually displayed at the experimenter's control desk by means of one-plane digital display units (Industrial Electronic Engineers, Model No. 10010).

Several important characteristics of the three channels are described below. The frequency responses of the right and left noise channels with the low-pass filters switched to the 7000-cps cut-off were measured at the terminal board in the quiet room. The response for each channel was flat ($\pm$ 0.2 dB) from 100 to 5000 cps and 3 dB down at the cut-off frequency. The rejection rate beyond cut-off was 18 dB per octave. The right, left, and bone channels had a frequency response that was flat ($\pm$ 0.5 dB) from 100 to 10,000 cps over the portions used for the tones. The electrical phase shift between the right and left channels was less than 2 degrees at 500 cps and about 3.6 degrees at 5000 cps. Measurements of harmonic distortion in the portion of the right and left channels used for the pulsed tones indicated that the first harmonic was about 35 to 40 dB below the fundamental over the frequency range that was used, while the higher harmonics were down 50 dB or more. Attenuator linearity was maintained at least to below 90 dB below 0.1 volt across the earphone terminals. At this level the electrical noise masked further measurements.

Earphones. Two types of earphones or receivers were used in this study. One type was a matched pair of dynamic earphones (Telephonics, Model TDH-39) mounted in small neoprene cushions (MX-41/AR). These receivers are commonly used in experimental and clinical studies. The other type was a pair of receivers manufactured by M. P. Pedersen, Copenhagen, Denmark*. Each of these receivers consists of a dynamic loudspeaker, seven inches in diameter, mounted in a metal sphere. The loudspeaker is supported within the sphere by means of felt padding. Soft rubber cushions are mounted on the spheres for circumaural contact with the head. These receivers are mounted on an adjustable crossbar and tripod pedestal.

In order to identify clearly the two types of receivers in the experiments to be reported, the dynamic earphones (Telephonics) will be called 'Conventional Receivers' and the dynamic loudspeakers will be called 'Pedersen Receivers'.

Sound pressure calibrations were performed for both sets of receivers by both continuous and discrete frequency methods. The additional instrumentation used for these calibrations was a sweep frequency oscillator, amplifier, and level recorder (Bruel & Kjaer (B&K) Audio Frequency Response and Spectrum Recorder, Model 3326), laboratory standard microphone (B&K, Model 4132), and associated cathode follower (B&K, Model 2612). Two types of acoustic couplers (artificial ears) were used for these

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*These receivers are on loan from Dr. Barry S. Elpern, University of Chicago Clinics, Chicago, Illinois.

calibrations. An ASA Type 1 coupler (B&K, Model DB 0161) was used for the conventional receivers, while an NBS-9A coupler (B&K, Model DB 0160) with an extended plate was used for the Pedersen receivers. The NBS-9A coupler was extended by means of an additional plate in order to provide a hard, flat surface against which the Pedersen receivers could rest for a good and reproducible acoustic seal.[12, 28]

All pressure calibrations were performed with 0.1 volt across the receiver terminals. Calibrations were done both prior to and at the completion of the experiment. No change in the calibrations of either sets of receivers was observed. The calibrations in sound pressure levels at the four experimental frequencies used in the experiments are shown for both sets of receivers in Table I.

Bone-conduction transducer. A commercially available dynamic-type bone-conduction transducer was used (Maico, Model C). The moving-iron piston, or drive-rod, of the transducer was extended in length by means of a plastic rod and terminated with a 1.5 cm^2 chamfered plastic tip. The cylindrical body of the transducer was fitted to a rubber sleeve which in turn was mounted in a housing of brass. The brass housing and the drive-rod terminated

Table I. Sound pressure levels (SPL's) in decibels re 0.0002 μbar for the two types of receivers at the four experimental frequencies. Source: 0.1 volt.

Frequency cps	CONVENTIONAL RECEIVERS Right	CONVENTIONAL RECEIVERS Left	PEDERSEN RECEIVERS Right	PEDERSEN RECEIVERS Left
250	107.2	106.6	98.6	102.4
500	107.2	106.3	100.4	101.4
1000	106.4	105.3	93.7	93.7
2000	104.3	104.9	85.8	86.4

with the plastic tip are shown in Fig. 3, and in more detail, in Fig. 6.

Figure 3 also shows the apparatus used to mount rigidly the transducer housing and assembly. The transducer could be extended to the required point of application on the head by means of a rack and pinion connected to a vernier adjustment knob. Both elevation and azimuth adjustments of the transducer could be made by sliding the transducer carriage along the steel semi-circular track and by rotation of the track around its vertical axis, respectively. The steel track in turn was mounted on a two-by-eight wooden beam which was suspended between two of the walls in the quiet room. Only adjustments of elevation were made in the experiments to be reported, and these were required because of the variations in frontal bone contours among the subjects. The subject was seated in a dental chair and, therefore, could easily be raised to the correct position relative to the transducer for application and positioning of the transducer on the head.

The apparatus used to provide a known coupling force between the transducer and the frontal bone site will be discussed in a later section. The measurement of the vibratory response of the bone-conduction transducer according to frequency, and the manner in which these measurements were carried out will be discussed in detail below.

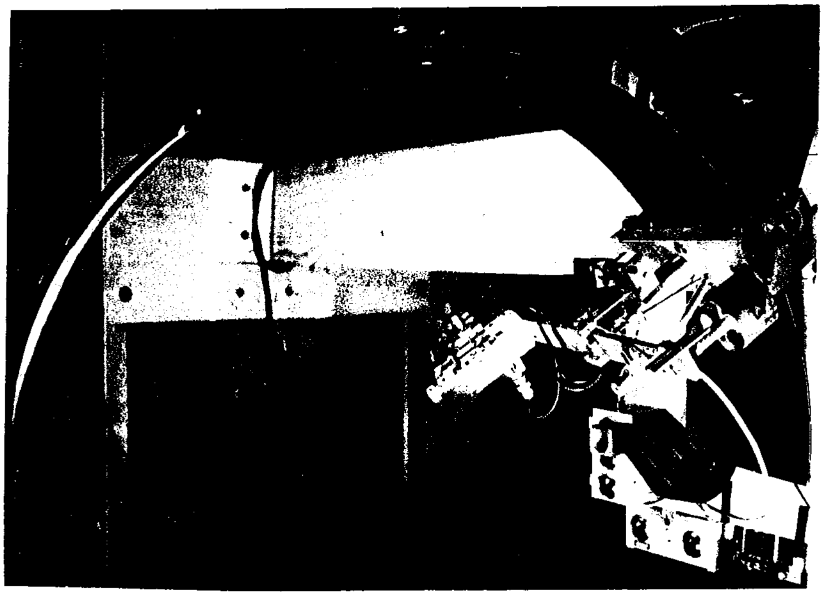

Fig. 3. Apparatus for mounting the bone-conduction transducer and pickup system.

Calibration and Monitoring of the bone-conduction transducer. Two measurement systems were used for the calibration of the bone-conduction transducer. One of the systems was also used to monitor the dynamic behavior of the transducer during the experiments. Measurements of the response of the transducer were obtained in terms of RMS velocity.

One measurement system was an accelerometer (B&K, Model 4308) and preamplifier-equalizer complement (B&K, Model 1606). The system could be used to obtain vibration measurements in terms of acceleration, velocity, or displacement. This system was highly accurate but could not be used to measure the velocity of the bone-conduction transducer when the transducer was coupled to a human head. However, this accelerometer system could be used to calibrate the bone-conduction transducer when the transducer was coupled to an 'artificial' load.

The other measurement system was a ceramic phonograph cartridge (Astatic, Model 51-1) and a preamplifier-equalizer complement which was specially constructed for this system. This system was designed for vibration measurements of the bone-conduction transducer when it was, in fact, coupled to the head. This system is called the 'pickup' system. Because the pickup system was the primary means of calibrating and monitoring the response of the bone-conduction transducer, it is described in detail below.

When a ceramic phonograph pickup is subjected to lateral motion (from its needle tracking the modulated grooves of a phonograph record for example), it produces an open-circuit voltage which is essentially proportional to the amplitude of this motion. In the present case, the pickup was attached to the housing of the bone-conduction transducer in such a way that its needle was forced to follow the rectilinear motion of the transducer's drive-rod. The output voltage of the pickup was then proportional to the amplitude of the vibrational motion of the bone-conduction transducer.

However, the rectilinear motion of the bone-conduction transducer, because of the dynamic characteristics of such devices, is more conveniently described in terms of velocity than in terms of amplitude. Therefore, it was decided to equalize the electrical output of the pickup so that its response could also be described in terms of velocity.

The electronic device used to equalize the pickup response consisted of four components: a cathode follower, two identical equalization stages, and a line amplifier. The cathode follower was used to match the impedance of the pickup to that of the first stage of variable equalization. The two equalization stages were connected in tandem. Each stage could alter the frequency characteristics of the input signal by increasing or decreasing the frequency response at pre-determined points in the frequency spectrum.[3] The output of the second stage was connected to a line amplifier with an output impedance of 600 ohms.

Now in order to obtain the necessary equalization of the pickup, a calibrated source of vibrational signals was required to drive the pickup. Two such calibrated sources were available in the form of phonograph records. One record (CBS Labs., Type STR-100) contained a sweep frequency band from 20 to 20,000 cps recorded at specified velocity levels. The other record (RCA, Type 12-5-50) was similar to the one above except it contained discrete frequencies. Both records were recorded with the following frequency characteristics: constant amplitude for frequencies up to 500 cps and constant velocity for frequencies beyond 500 cps.

The output of an ideal velocity-sensitive pickup when reproducing the frequency characteristics of the two records would be as follows: an output level increasing with frequency at the rate of 6 dB per octave for frequencies below 500 cps, and a constant output level for frequencies above 500 cps. This ideal response is illustrated by the dashed line in Fig. 4. The solid line, on the other hand, shows the response of the pickup system and it is

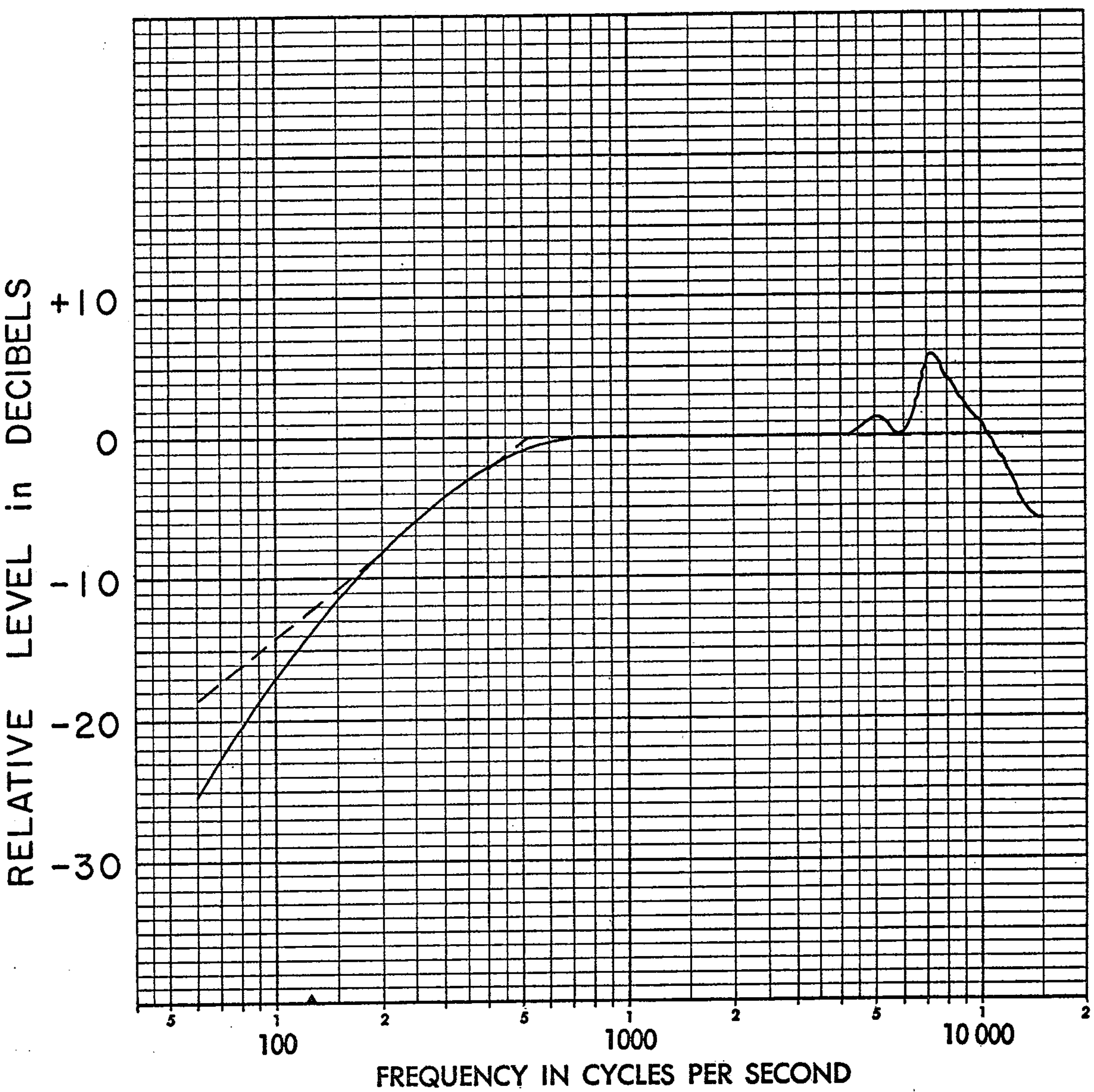

Fig. 4. The mean response of the velocity-sensitive pickup system obtained from two calibration records as sources. The ideal response is shown by the dashed lines, while the solid line shows the actual response.

the mean of the responses obtained from the two records. The agreement between the frequency-response characteristics obtained using the two records was excellent (± 1 dB between 200 and 6000 cps). Since the experiments to be reported were limited to test frequencies between 200 and 4000 cps the deviations of the measured curve from the theoretical curve shown in Fig. 4 are of no concern.

The relations between the output voltages of the pickup system and the velocities on the records were obtained from measurement of the voltages produced by the recorded velocities. These recorded velocities were specified by the manufacturers of the records. The entire pickup system was adjusted so that an output of 1.0 volt was obtained for an input velocity of 1.0 cm/sec.

It was assumed that the calibration of the pickup system as described above would be maintained when the pickup itself was connected to the drive-rod of the bone-conduction transducer. Therefore, in order to test this assumption, comparison calibrations were obtained for the bone-conduction transducer by means of the pickup and the accelerometer systems.

The comparison calibrations of the bone-conduction transducer were obtained with an artificial load coupled to the transducer's drive-rod. As previously mentioned, this was necessary because the accelerometer system could not be used when a human head provided the load. With the pickup and accelerometer attached to the transducer, a 500 gram cylindrical mass was mounted concentrically on the tip of the drive-rod. The comparison calibrations were performed with the transducer in the position as shown in Fig. 7.

In general, the results of these calibrations between the pickup and the accelerometer systems were in good agreement between 200 and 4000 cps. However, the calibration response obtained by the pickup system exhibited minor resonant peaks at several frequencies above 800 cps. These resonant peaks were attributed to the artificial load, because they were not observed when the head was used as a load. Assuming that these minor resonances can then be neglected in this case, the difference between the calibrations obtained by the two systems for the transducer with the artificial load was ± 1 dB from 200 to 4000 cps.

Therefore, it was concluded that the pickup system was accurately calibrated ($\pm$ 1 dB) over the frequency range from 250 to 2000 cps which was the range used in the experiments to be reported.

A calibration curve for the bone-conduction transducer coupled to a human head was obtained by means of the pickup system. For these measurements the transducer was in place on the frontal bone and a coupling force of 750 grams was used.

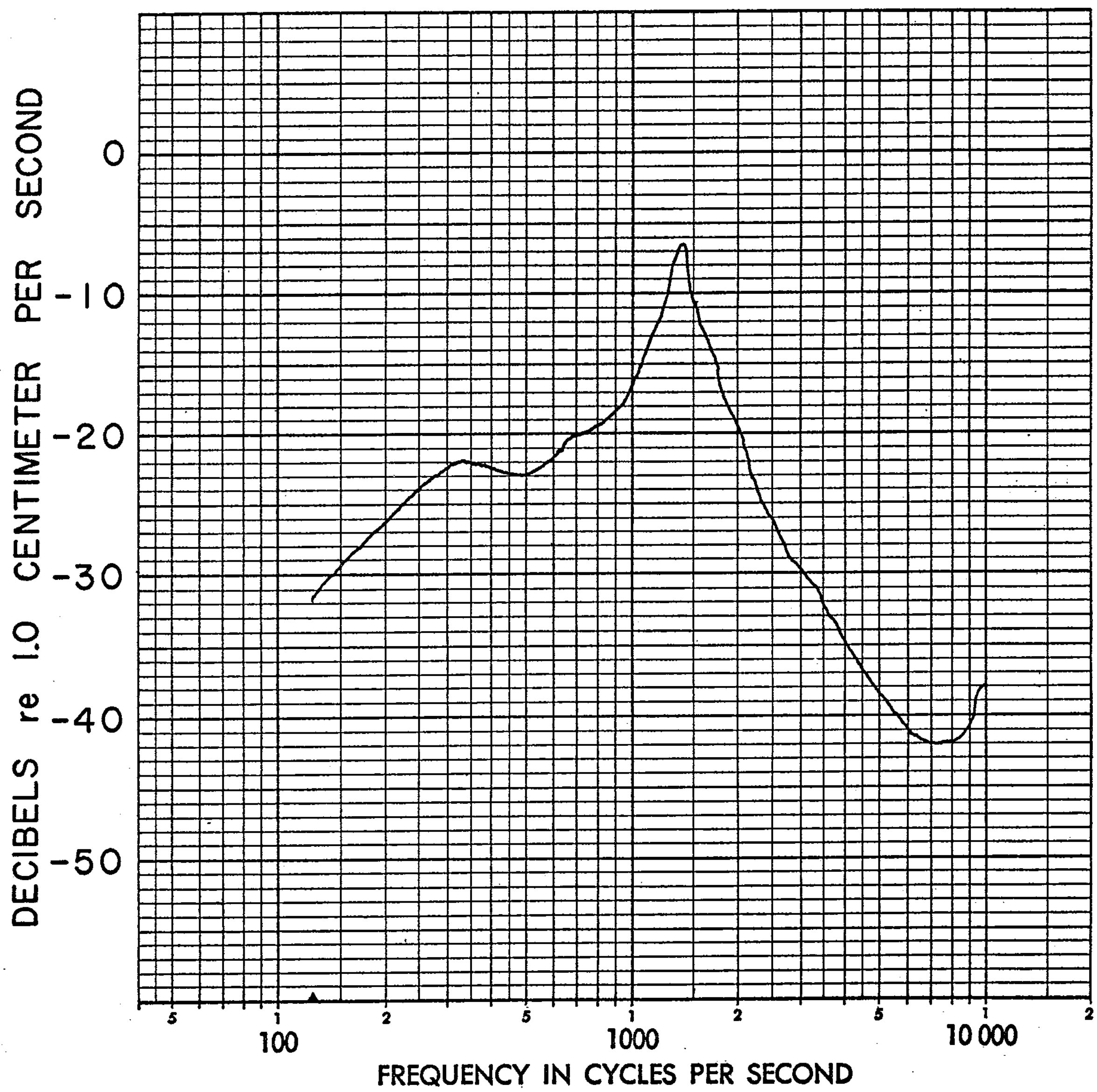

Fig. 5. Calibration curve for the bone-conduction transducer obtained by means of the pickup system. The transducer was in place on the frontal bone and a coupling force of 750 grams was used.

The results are shown in Fig. 5. It should be noted that the calibration curve indicates that the fundamental resonant frequency of the bone-conduction transducer is about 1400 cps. In contrast, the resonant frequency obtained for the calibrations done with the artificial load was about 800 cps. The upward frequency shift of the resonant peak when the head was used as the load on the transducer is probably due to a basic characteristic feature of the transducer. This characteristic feature is that the vibratory response of the transducer is not independent of the applied load. However, with a coupling force of 750 grams and the head as a load the stability of the response of the transducer was good. Only minor variations in the response curve shown in Fig. 5 were observed from head to head.

As a further precaution against the possibility that the calibration of the bone-conduction transducer might change during the actual experiments, velocity calibration measurements were performed prior to and at the completion of each experimental session during which bone-conduction thresholds were determined. Therefore, any shift in the resonant frequency (and, therefore a shift of the response curve as a whole) would be included in these calibration measurements.

The manner in which the pickup was mounted on the housing of the bone-conduction transducer and the location of the pickup

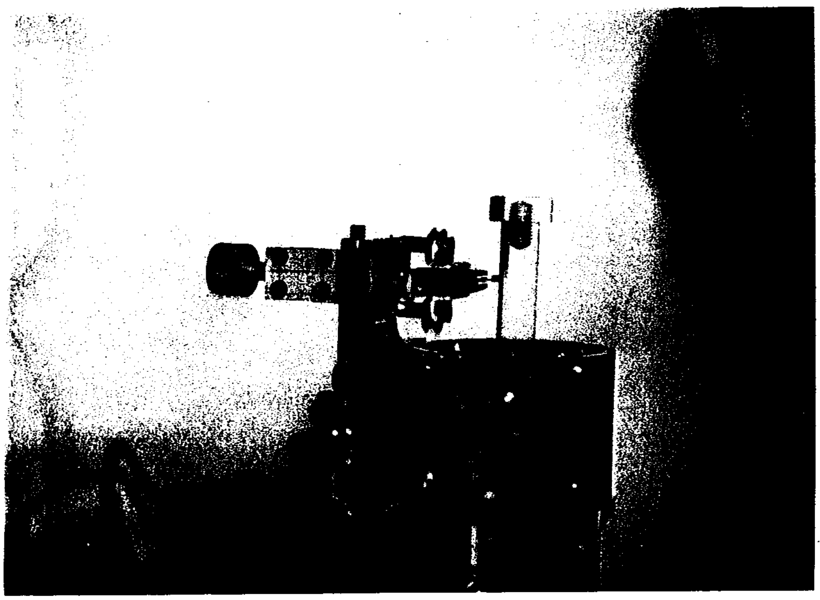

Fig. 6. Illustration of the mechanical arrangement used to mount the pickup on the bone-conduction transducer. The needle of the pickup can be seen mounted in the brass stud on the drive-rod.

relative to the drive-rod of the transducer are shown in Fig. 6. The pickup was mounted so that the needle was perpendicular to the drive-rod. The needle was fitted into a small brass stud which in turn was mounted on the drive-rod near its tip. The mounting arrangement provided for movement of the pickup in three dimensions (parallel, perpendicular, and lateral) relative to the drive-rod. This was necessary in order to align the needle accurately and the stud into which it must fit. The pickup was mechanically isolated from its adjustable mounting arrangement by means of rubber washers.

<u>System for maintaining the coupling force</u>. The system used to maintain the coupling force between the bone-conduction transducer and the frontal bone of the subject's head is shown in Fig. 7. This system and one which was investigated for possible use are described below.

The housing of the transducer and pickup was mounted on one end of a brass beam. An adjustable counterweight was mounted on the opposite side and at the other end of the beam. The beam itself was supported at its mid-point by means of ball bearings in a brass fork. The beam assembly was balanced by adjustment of the counter-weight so that at rest, without a load on the transducer,

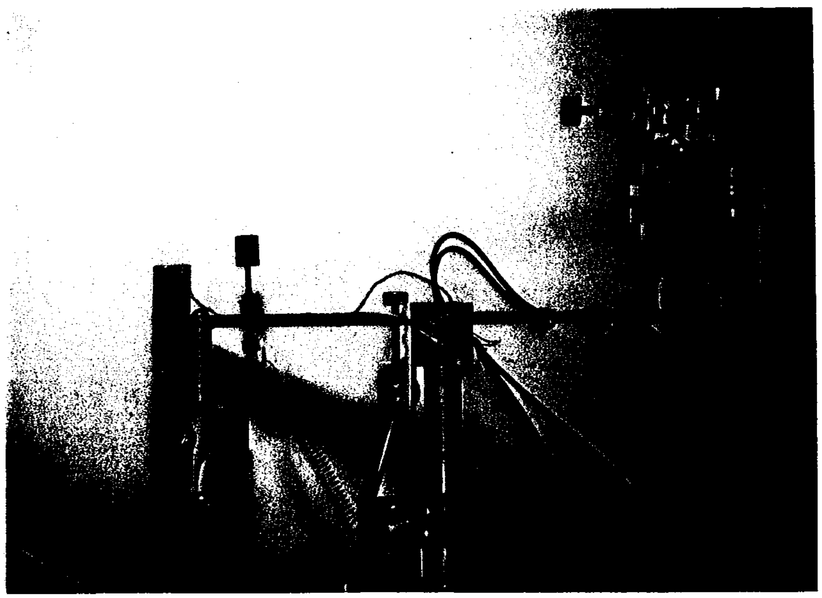

Fig. 7. Illustration of the mechanical system used to maintain the coupling force between the transducer and the head. Coupling force calibrations were obtained with the transducer assembly in this position.

it would remain perpendicular to the fork. The beam assembly maintained this balanced position when it was placed in the normal experimental position which is shown in Fig. 3.

In order for the transducer to apply a force against the head, a spring was connected to one end of an adjustable screw which in turn was threaded on the counter-weight end of the beam. The other end of the spring was connected to an adjustable rod which in turn was connected to the fork. With the transducer assembly in the position as illustrated in Fig. 7, a 750 gram mass was attached to the tip of the drive-rod at the transducer end of the beam. The spring was then adjusted to produce an equal and opposite force to that of the mass. Thus, the beam remained in its balanced position. With the transducer assembly positioned for bone-conduction measurements, as illustrated in Fig. 3, and the transducer coupled to the head of a subject, a force of 750 grams was required by the subject's to maintain the beam in the balanced position.

If the beam became unbalanced due to inadvertant foreward or backward movements of the subject's head, the fact that the beam was unbalanced could be visually detected by the subject. Three lights mounted below and in back of the transducer housing provided the relevant information. These lights were connected to a three-position switch located on the counter-weight end of the beam. The switch was adjusted so that when the beam was balanced a green light was on. Unbalancing the beam by 25 grams in either direction caused either one of two other lights to be switched on. Thus, the subject could maintain the coupling force at 750 grams ($\pm$ 25 grams).

Another coupling force system which included a device to measure the force at the tip of the drive-rod when it was in contact with the head was investigated and this system is described below.

The system was similar to the one described above, except the tip of the drive-rod of the transducer was replaced by a small condenser microphone. The condenser microphone was similar in design to one described by Bekesy[4]. The microphone was to be used to measure accurately the coupling force between it (and in turn the drive-rod of the transducer) and the head, when the transducer was in contact with the head.

Such a system should measure the actual coupling force. These measurements in turn could be used to assess more accurately the coupling force required to maintain the lowest and least variable bone conduction thresholds at low frequencies. The investigation of this system was terminated because requirements for sufficient accuracy and stability could not be realized.

GENERAL PROCEDURE

Threshold determinations. A method of adjustment was used. The subject was instructed to obtain, by bracketing, the points where the pulsed-tone signal was just audible and had some tonality. For this purpose, the subject manipulated a 1-dB/step attenuator and could, in addition, switch in 10 dB of attenuation to verify the tentitive point obtained by adjustment of the 1-dB/step attenuator. Since the dial on the subject's attenuator was unmarked and the experimenter shifted the amount of attenuation in his attenuator from trial to trial in a haphazard fashion, the subject was required to base his decision on the input to his ear. A light was used to signal the start of each trial to the subject. The subject, upon deciding that the level of the pulsed tone met the criterion, signalled the experimenter by means of another light. The experimenter read the setting of the subject's attenuator as well as his own from the digital display units, and then signalled the subject to reset his attenuator by means of a third light. A single threshold determination was usually completed in less than 20 sec.

All threshold determinations were obtained with the subject seated in the dental chair. In the case of the bone-conduction threshold determinations, the chair was raised vertically until the final positioning and application of the transducer could be made on the head. The subject's head was maintained in the correct position by means of a head rest, which was adjusted to oppose the 750 gram force exerted by the transducer when it was coupled to the head. The required elevation of the transducer carriage, with respect to the horizontal, necessary to obtain perpendicular positioning of the tip of the drive-rod to the frontal bone site was maintained for each subject throughout the experiments. The exact location of the tip of the drive-rod on a subject's frontal bone was easily replicated from trial to trial. This was possible because of the coloration and deformation of the skin at the point of application of the tip when it was coupled to the head.

Subjects. Five young adults with normal hearing were trained and employed as subjects. Three of the subjects participated in all the experiments; of the remaining two, one subject completed only Experiment I, while the other subject participated in both Experiments II and III.

Experimental Frequencies and Noises. The same set of frequencies was used in all of the experiments to be reported. These frequencies were 250, 500, 1000, and 2000 cps. Low-pass noise but with two different cut-off frequencies were used for the blocking and masking noises. The cut-off frequencies for the two kinds of low-pass noises were 7000 and 7000 cps. The 7000-cps low-pass blocking and masking noises were used in conjunction with the 250- and 500-cps signals, while for the 1000- and 2000-cps signals, 7000-cps low-pass noises were used.

CHAPTER III

INTRODUCTION

Experiment I was conducted to evaluate the method for obtaining monaural thresholds for bone-conducted signals masked by air-conducted noises. The method, it will be recalled, required a masking noise at the ear at which thresholds for bone-conducted signals are to be determined and a blocking noise at the ear at which the effects of the bone-conducted signals are to be eliminated.

In the development of this method, as described in Chapter I, the results of the study by Weston and Miller[32] suggested that the blocking noise must be both independent of and about 25 dB higher than the masking noise in order to determine monaural masked thresholds at the ear receiving the masking noise. Weston and Miller showed, for the case of air-conducted 500-cps signals, that the relations between the blocking and masking noises described above were indeed necessary in order to obtain monaural masked thresholds. The 25-dB difference in level between the blocking and masking noises provided a blocking noise of sufficient level to effectively eliminate that ear from being stimulated by the signal; the statistical independence of the blocking noise from the masking noise resulted in the threshold at the ear receiving the masking noise not being influenced by the blocking noise.

Therefore, Experiment I was designed to firmly establish the fact that the relations between the blocking and masking noises necessary for the determination of monaural thresholds for air-conducted 500-cps signals also hold for the case of bone-conducted 500-cps signals as well as for bone-conducted signals of other frequencies. Thus, signals were delivered by bone conduction, while masking and blocking noises were delivered by air conduction.

The design of the experiment included two variables: (1) the difference in level between the blocking and masking noises and (2) the correlation between these noises; that is, the noises had either a positive correlation of plus one or they were statistically independent (uncorrelated). In the notation described in Chapter 1 and illustrated in Fig. 1, these conditions were $N_{+1,\ x}S_{bc}$ and $N_{u,\ x}S_{bc}$.

APPARATUS and PROCEDURE

The right, left, and bone channels, as described in Chapter II and shown in Fig. 2, and the Conventional Receivers (TDH-39 dynamic earphones mounted in MX-41/AR cushions) were used in this experiment. The spectrum levels (re: 0.0002 μbar) of the masking noises along with the range of the spectrum levels of the blocking noises are shown in the last two columns of Table II for each of the four test frequencies. The bone-conduction thresholds were measured in terms of decibels of attenuation (with 0 dB equal to 3.16 volts across the bone-conduction transducer's terminals) of the bone-conduction signal present at threshold.

Many of the procedures used in this experiment have been previously described (see General Procedures in Chapter II) however, those aspects of the procedure that were unique to this experiment are described below.

One block of the experimental design is shown in Table II. A block consisted of four units; one for each frequency. Two stimulus conditions, $N_{u,\,x}S_{bc}$ and $N_{+1,\,x}S_{bc'}$, were used and they are given in column three of Table II. Column four indicates the number of values of $\underline{x}$ per condition, column five the number of

Table II. Table for one block of the experimental design for Experiment I.

Units	Frequency cps	Condition	Number of values of x	Thresholds per condition	Total thresholds per unit	Spectrum Level in decibels: Masking noise	Spectrum Level in decibels: Blocking noise
		QAT[a]		1		OFF	+41
1	250	$N_{u,x} S_{bc}$	5	1	11	+41	+41to+81
		$N_{+1,x} S_{bc}$	5	1		+41	+41to+81
		QAT		1		OFF	+24
2	500	$N_{u,x} S_{bc}$	5	1	11	+31	+24to+64
		$N_{+1,x} S_{bc}$	5	1		+31	+24to+64
		QAT		1		OFF	+4
3	1000	$N_{u,x} S_{bc}$	5	1	11	+11	+4to+44
		$N_{+1,x} S_{bc}$	5	1		+11	+4to+44
		QAT		1		OFF	+5
4	2000	$N_{u,x} S_{bc}$	5	1	11	+11	+5to+45
		$N_{+1,x} S_{bc}$	5	1		+11	+5to+45

[a]QAT stands for quiet absolute threshold.

thresholds per condition, and column six the total number of thresholds per unit. Column seven and eight show the spectrum levels of the masking noise (MN) and the blocking noise (BN), respectively, for each condition. The blocking noises were varied in 10-dB steps. Each of the four subjects made each of the threshold determinations in a block on five occasions, thus, there were five replications of a block for each subject. Within each replication the order of units was randomized for each of the subjects. Each unit began with a determination of the quiet absolute threshold (QAT) for the right ear, with appropriate blocking noise level to the left ear, then the binaural noise and signal conditions were run in a randomized order. Each subject completed two units during an experimental sitting.

RESULTS

The results for Experiment I are shown in the four panels of Fig. 8 for the four signal frequencies 250, 500, 1000, and 2000 cps. The ordinates are bone-conduction thresholds in decibels of attenuation (for 0 dB equal to 3.16 volts across the bone-conduction transducer's terminals). The abscissae are the spectrum levels (re: 0.0002 ubar) for the blocking noises (BN). The parameter is the correlation between the blocking and masking noises. Each datum point represents the mean of 20 threshold determinations. The open squares represent the thresholds for the $N_{u,x}S_{bc}$ condition, noises independent, while the filled squares represent the thresholds for the $N_{+1,x}S_{bc}$ condition, noises identical except for amplitude. The quiet thresholds are not shown. The arrows to the left on each panel indicate those data points for which the blocking and masking noise levels were equal, while the arrows to the right on each panel show those points for which the level of the blocking noise was 25 dB higher than that of the masking noise.

The curves show that as the blocking noise is increased from a level equal to that of the masking noise (the arrows to the left) the effect of the bone-conducted signal at the ear receiving the blocking noise is progressively eliminated until a plateau is reached. Further increases of the level of the blocking noise over that of

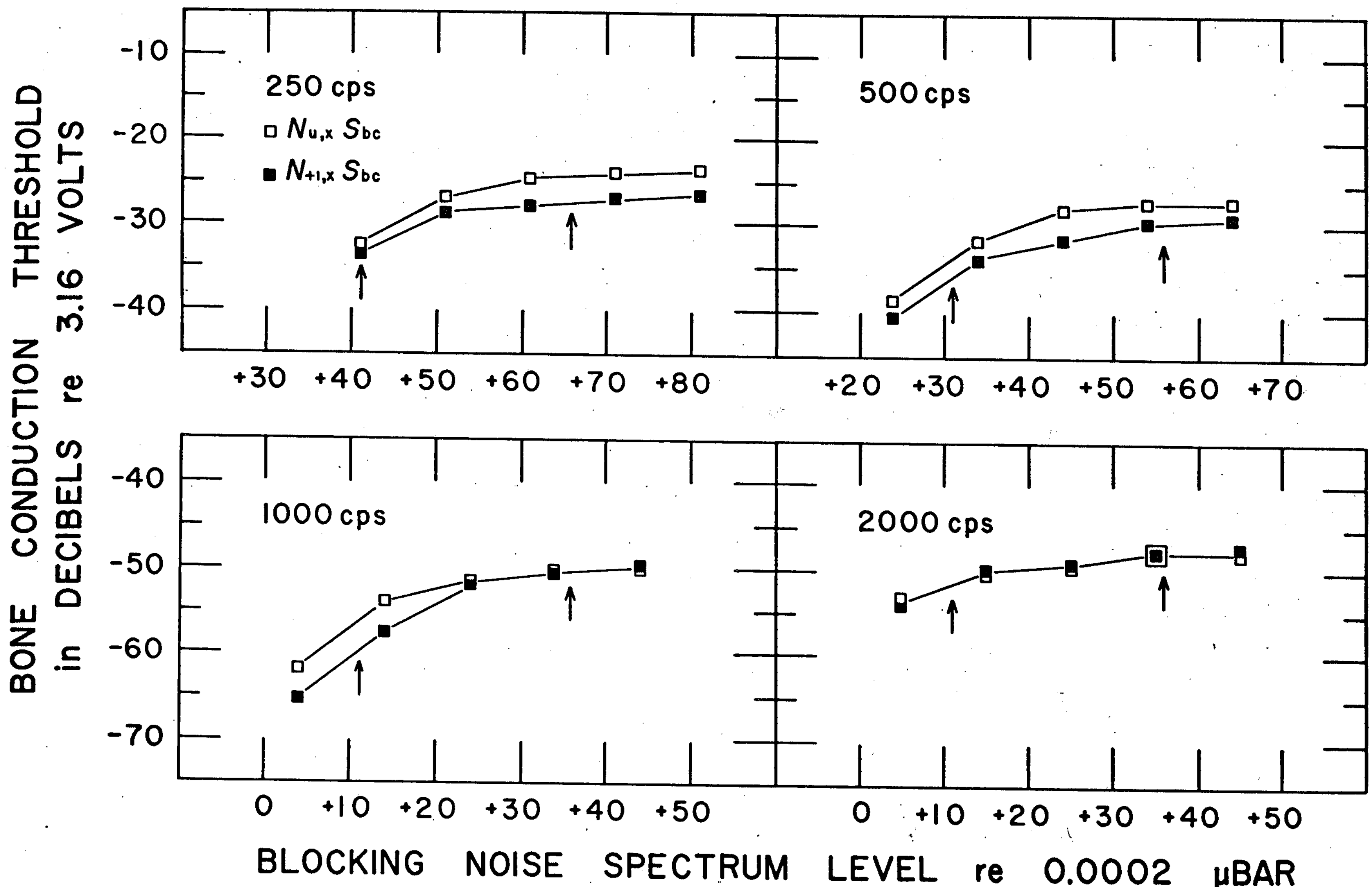

Fig. 8. The results for Experiment I. Masked thresholds for bone conduction as a function of blocking noise level are shown for the four signal frequencies. The arrows to the left on each panel indicate those data points for which the blocking and masking noises are equal, while the arrows to the right on each panel show those points for which the level of the blocking noise was 25 dB higher than that of the masking noise.

the masking noise seems to have little effect on the signal threshold. Thus, these facts suggest that the effects of the signal have been eliminated from the ear receiving the blocking noise when the level of the blocking noise is about 25 dB higher than that of the masking noise and that under these conditions the threshold is being determined only at the ear receiving the masking noise. This conclusion seems to be correct for all signal frequencies no matter whether the noises at the two ears are perfectly correlated or independent of one another.

On the other hand, thresholds for independent noises ($N_{u,\ x}S_{bc}$) are higher than for correlated noises ($N_{+1,\ x}S_{bc}$), especially for 250- and 500-cps signals. The difference in thresholds for these signals appears to be independent of the level of the blocking noise. The difference in thresholds for the 1000-cps signal is smaller and is a function of the level of the blocking noise, while for the 2000-cps signal the difference is almost nil.*

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* It can be seen in Fig. 8 that all of the curves, except the ones for the 250-cps signal, do not extend much beyond that point on the curves (the arrows to the right) for which the level of the blocking noise was 25 dB higher than that of the masking noise. As a result little information was obtained concerning the extent of the plateau of these curves beyond the arrows to the right. The extent of the plateau was limited because of a mechanical failure of the receiver that was used to provide the blocking noise. Unfortunately, the mechanical failure and the resultant change in the level of the acoustic output of the receiver was not detected until Experiment I was completed.

The mechanical failure of the receiver was due to the drying out of the adhesive material which held the central dome of the receiver's diaphragm in place. As a result the dome became separated from the diaphragm, and thereby provided a large acoustic leak into the cavity behind the diaphragm. The acoustic characteristics and, as a direct consequence, the acoustic output of the receiver were drastically altered by the leak. Calibrations performed on the receiver, before it was dismantled for inspection, indicated that the sound pressure levels (SPL's) were lower by about 7 dB for the 500-, 1000-, and 2000-cps signals and about 18 dB for the 250-cps signal than those SPL's obtained from similar calibrations made prior to the receiver's mechanical failure.

The spectrum levels for the blocking noises for the 500-, 1000-, and 2000-cps signals that are shown in Fig. 8 are corrected for the 7 dB change in the calibration levels. These adjustments in the level of the blocking noise account for the limited extent of the plateau regions for these three signal frequencies.

At 250 cps the change in the receiver's calibration was so drastic, that is 18 dB, that the experiment was repeated. A new set of matched receivers were used. The results shown in Fig. 8 are those obtained using the new set of matched receivers; the original data for this signal were discarded.

The curves, then, as shown in Fig. 8 for the 250-cps signal represent 'clean' data, while the curves for the 500-, 1000-, and 2000-cps signals represent data that are probably contaminated by other unknown effects on the acoustic output of the receiver due to its mechanical failure.

CONCLUSIONS

Even with the factors described in the preceeding footnote taken into account, the curves shown in Fig. 8, the results of Weston and Miller[32], and those of Experiment II to be reported in the next section, support the notion that the determination of monaural masked thresholds for bone-conducted signals requires a contralateral blocking noise that is both independent of and about 25 dB higher in level than the masking noise.

FURTHER OBSERVATIONS

Other observations will concern a general feature of the curves in Fig 8. Consider the curve for the correlated noises ($N_{+1}, {}_xS_{bc}$), for the 500-cps signal. As the blocking-noise level increases, the threshold gradually rises to a plateau. Now Weston and Miller did a similar experiment, but their binaural signals were delivered by air conduction. Those air-conducted signals were known to be identical in all respects at the two ears. In that case, the threshold values gradually decreased to a plateau. This difference in direction of the curve in Experiment I and in that of Weston and Miller casts doubt on the assumption that the effects of a bone-conducted signal are identical at the two ears, as was the case for air conduction.

It is not possible to determine from the present experiment whether the bone-conducted signals at the two ears differ in amplitude, phase, or both. Therefore, any inferences made concerning the details of the relations between the signals at the two ears for the bone-conduction case would lie in the realm of conjecture. The experiment, after all, was designed to demonstrate that for bone conduction the effects of the signal at one ear could be eliminated, and not to study the resultant interaural interactions for signals at both ears.

CHAPTER IV

INTRODUCTION

Experiment II was conducted to ascertain which of several possible air-conduction thresholds would be the most appropriate for comparison with the bone-conduction threshold, when both masking and blocking noises are used, and how they were related to the usual masked threshold, namely monaural signal with monaural noise.

The conditions of the experiment were as follows: (1) the conventional masked threshold obtained with both signal and noise delivered to the right ear ($N_m S_m$); (2) same as (1) but an independent noise added to the left ear at a level 25 dB higher than the original noise ($N_{u,25} S_m$); and (3) same as (2) but an additional signal presented to the left ear, and the new signal maintained identical in all respects to the signal in the right ear ($N_{u,25} S_{0,0}$). All signals were delivered by air conduction.

APPARATUS and PROCEDURE

The right and left noise and tone channels, as described in Chapter II and shown in Fig. 2, and the Conventional Receivers (TDH-39 dynamic earphones mounted in MX-41/AR cushions) were used in this experiment. The spectrum levels (re 0.0002 ubar) for the masking noises were +29.7, +19.7, +13.9, and +11.8 for the signal frequencies of 250, 500, 1000, and 2000 cps, respectively. The spectrum levels of the blocking noises for the binaural noise conditions were 25 dB higher in level than those of the masking noises.

Several of the procedures used in this experiment were described previously (Chapter II), however, those aspects of the procedure that were unique to this experiment will be described here. A single block of the experiment consisted of four units, one for each frequency. Within each unit two threshold determinations were obtained for each of the three conditions. Each subject completed one experimental block during a sitting on five occasions. Thus, there were five replications for each experimental block, and, therefore, 40 threshold determinations were obtained for each combination of condition and frequency. The order of the units within a block and the order of the conditions within a unit were separately randomized.

Each unit began with a determination of the quiet threshold for each ear, then the three noise conditions were run, and finally, the determinations of the quiet thresholds were repeated.

RESULTS

Table III shows the results for each of the three conditions. The results are each the mean of 40 threshold determinations and they are expressed in sound pressure levels (SPL's). The differences between the thresholds obtained for the monaural noise condition, $N_m S_m$, and those obtained for each of the two binaural noise conditions, $N_{u,25} S_m$ and $N_{u,25} S_{O,O}$, are also shown. The mean difference between the thresholds for the condition $N_m S_m$ and those for the condition $N_{u,25} S_m$ is -0.475 dB, while the mean difference between the thresholds for the condition $N_m S_m$ and those for the condition $N_{u,25} S_{0,0}$ is -0.45 dB. All of the differences (except for one condition at 2000 cps) fall in the same direction. This indicates that the two binaural conditions produce a very small (about 0.5 dB) change in the monaural masked threshold. It should be noted that in the case of the condition $N_{u,25} S_{0,0}$ the signal at the left ear has no effect on the threshold. Thus, one can infer that the threshold was obtained for the signal at the right ear.

Table III. Results of Experiment II for the three conditions in terms of sound pressure level (SPL) according to frequency (cps). The difference in decibels between the monaural condition ($N_m S_m$) and the two binaural conditions is also shown.

	250		500		1000		2000	
Conditions	SPL	Diff.	SPL	Diff.	SPL	Diff.	SPL	Diff.
$N_m S_m$	48.0		37.5		32.2		30.8	
$N_{u,25} S_m$	47.8	-0.2	36.6	-0.9	31.5	-0.7	30.7	-0.1
$N_{u,25} S_{0,0}$	47.2	-0.8	37.0	-0.5	31.7	-0.5	30.9	+0.1

DISCUSSION and CONCLUSIONS

These results strongly support those of Weston and Miller[32], which were obtained for a 500-cps signal, and they provide a firm basis for extending their conclusions to other frequencies. Thus it appears that a noise in one ear has little or no effect on the masked threshold for a signal in the other ear if these noises are independent; that is, from separate noise generators. This is true even if the noise in the ear which does not receive the signal, that is the blocking noise, is 25 dB higher in level than that of the masking noise in the ear which does receive the signal. Further, if signals identical in all respects are delivered to the two ears, the one presented to the ear receiving the blocking noise has no effect on the threshold for the signal at the other ear.

These facts provide additional support for the rationale behind the method to be used in Experiment III to obtain monaural thresholds for bone-conducted signals masked by air-conducted noise. Moreover, the results of the present experiment show that the signal thresholds for the three conditions which were tested are nearly the same and, therefore, one may measure such thresholds using the most convenient or simple procedure.

FURTHER OBSERVATIONS

There is a possibility that the conclusions given in the previous section are only correct if the blocking noise is presented to the left ear while the masking noise is presented to the right ear. Since all of the experiments reported in this study were carried out with one arrangement of the blocking and masking noises, the conclusions drawn from one experiment bear directly on the other. However, it seems unlikely that the results would differ if the blocking noise were presented to the right ear and the masking noise were presented to the left ear, but the possibility must be noted for the unwary.

CHAPTER V

INTRODUCTION

This experiment made extensive use of the method for the determination of monaural thresholds for bone-conducted signals masked by air-conducted noise. It was believed that extensive use of the method would test the accuracy of the method, and perhaps, reveal some of its deficiencies or, at least, indicate relevant factors that had not yet been anticipated.

The method, it will be recalled, requires a masking noise at the ear for which thresholds for bone-conducted signals are to be obtained and a blocking noise at the ear for which the effects of the bone-conducted signals are to be eliminated. On the basis of the conclusions of Experiments I, II, and those of Weston and Miller[32], the blocking noise is required to be both independent of and 25 dB higher in level than that of the masking noise.

Since there were no reasons other than its novelty to doubt the method, this experiment was designed to provide several kinds of information. These objectives are classified and described below.

(1) Masking functions. The experiment was designed to test the hypothesis that the shapes of the curves relating monaural masked threshold to noise level are identical for both air- and bone-conducted signals.

(2) The determination of masking. The experiment was designed to determine, for a given air- and bone-conduction transducer configuration, the amount of noise required to produce a specific amount of masking of a bone-conducted signal at an ear.

(3) Physical measures of the threshold signal. The experiment provided for the calibration in physical units of both the air- and bone-conduction transducers. Thus, physical measures could be calculated for both air- and bone-conducted signals when they are set to threshold intensity.

(4) Linearity of the bone-conduction transducer. The experiment was designed to obtain psychophysical measures of the linearity of the bone-conduction transducer as a function of input.

(5) The occlusion effect. The experiment was designed to assess the 'occlusion effect' on the masked as well as the quiet threshold of bone-conducted signals.

(6) Variability of the threshold signal. The experiment provided measures of the variability of thresholds obtained by bone conduction in the quiet and in masking noise.

One set of experimental procedures provided all of the information described above.

APPARATUS and PROCEDURE

In this experiment the right, left, and bone channels were used in conjunction with the Conventional and Pedersen Receivers. The receivers and the apparatus were described in Chapter II, and the block diagram of the apparatus is shown in Fig. 2.

The bone-conduction thresholds were measured in decibels of attenuation (with 0 dB = 3.16 volts across the bone-conduction transducer's terminals) of the bone-conducted signal. These measurements were later transformed to rms velocities. This was possible because of the procedure for this experiment. These calibrations were carried out with the bone-conduction transducer coupled to the subject's frontal bone site with 750 grams force. Then a continuous signal was fed to the transducer at 3.16 volts across its terminals (with the subject's and experimenter's attenuators both set for zero attenuation). The output of the pickup system (as described in Chapter 2) was measured in decibels (re 1.0 volt) with the AC voltmeter. It will be recalled that the pickup system was adjusted so that an output of 1.0 volt was obtained for an input of 1.0 cm/sec rms. Thus, velocity measurements in dB were obtained from the pickup system for a constant voltage at the input of the transducer. The actual velocity in decibels of the signal present at threshold was simply the calibration measurement minus the total attenuation introduced by the subject's and experimenter's attenuators.

The air-conduction thresholds were measured in decibels of attenuation (with 0 dB = 0.1 volt across the receiver's terminals). These measurements were later transformed to sound pressure levels (SPL's) by means of the calibrations for the two sets of receivers as shown in Table I.

The general procedures used in this experiment have been described previously (see General Procedure, Chapter 2); however, those aspects of the procedure what were peculiar to this experiment are described below.

One block of the experimental design is shown in Table IV for the Conventional Receivers and in Table V for the Pedersen Receivers. Each subject completed five blocks for the

Conventional Receivers, Table IV, and five blocks for the Pedersen Receivers, Table V. Thus, each subject made five replications of each of the two types of blocks. The sequence in which the blocks were presented to each subject is given in Table VI. The blocks are identified by the receivers that were used; Conventional Receivers (CR) or the Pedersen Receivers (PR). Because the blocks shown in Tables IV and V are identical except for the receivers and the noise levels, a description of one table will hold for both.

A block consisted of four units; one for each frequency. Column three shows the signal pathway, bone or air conduction, for each of the conditions shown in column four. For the bone-conduction pathway the conditions are quiet absolute threshold (QAT) and $N_{u, 25}S_{bc}$, while for the air-conduction pathway they are QAT and N_mS_m. Column five indicates the number of thresholds per condition, while column six shows the total number of thresholds per unit. The spectrum levels for the masking noise are shown in column seven. In more detail column seven shows for the bone-conducted signals that the quiet thresholds (QAR's) were obtained for each ear with the spectrum level of the

Table IV. One block of the experimental design for the Conventional Receivers for Experiment III. See text for a full description.

Units	Frequency cps	Signal	Condition	Thresholds per condition	Thresholds per unit	Masking Noise Spectrum Level
1	250	Bone	QAT[a]	2	10	OFF (BN=+29)[b]
			$N_{u,25}$ S_{bc}	2		+20, +30, +40, +50
		Air	QAT	2	6	OFF
			N_m S_m	2		+30, +50
2	500	Bone	QAT	2	10	OFF (BN=+19)
			$N_{u,25}$ S_{bc}	2		+10, +20, +30, +40
		Air	QAT	2	6	OFF
			N_m S_m	2		+20, +40
3	1000	Bone	QAT	2	10	OFF (BN=+8)
			$N_{u,25}$ S_{bc}	2		+4, +14, +24, +34
		Air	QAT	2	6	OFF
			N_m S_m	2		+14, +34
4	2000	Bone	QAT	2	10	OFF (BN=+7)
			$N_{u,25}$ S_{bc}	2		+2, +12, +22, +32
		Air	QAT	2	6	OFF
			N_m S_m	2		+12, +32

[a] QAT stands for quiet absolute threshold which was determined for each ear.

[b] Indicates the blocking noise (BN) level used for QAT determinations at the other ear.

Table V. One block of the experimental design for the Pedersen Receivers for Experiment III. See text for a full description.

Units	Frequency cps	Signal	Condition	Thresholds per condition	Thresholds per unit	Masking Noise Spectrum Level
1	250	Bone	QAT[a]	2	10	OFF (BN=+35)[b]
			$N_{u,25}\ S_{bc}$	2		+21, +26, +31, +36
		Air	QAT	2	6	OFF
			$N_m\ S_m$	2		+26, +36
2	500	Bone	QAT	2	10	OFF (BN=+24)
			$N_{u,25}\ S_{bc}$	2		+13, +18, +23, +28
		Air	QAT	2	6	OFF
			$N_m\ S_m$	2		+18, +28
3	1000	Bone	QAT	2	10	OFF (BN=+16)
			$N_{u,25}\ S_{bc}$	2		+1, +11, +21, +31
		Air	QAT	2	6	OFF
			$N_m\ S_m$	2		+11, +31
4	2000	Bone	QAT	2	10	OFF (BN=+29)
			$N_{u,25}\ S_{bc}$	2		+3, +13, +23
		Air	QAT	2	6	OFF
			$N_m\ S_m$	2		+13, +23

[a] QAT stands for quiet absolute threshold which was determined for each ear.

[b] Indicates the blocking noise (BN) level used for QAT determinations at the other ear.

Table VI. Table of receiver sequence by replications for each subject in Experiment III.

Replications	1		2		3		4		5	
Subjects 1 & 2	CR[a]	PR[b]	PR	CR	CR	PR	PR	CR	CR	PR
Subjects 3 & 4	PR	CR	CR	PR	PR	CR	CR	PR	PR	CR

[a]CR stands for Conventional Receiver.

[b]PR stands for Pedersen Receiver.

blocking noise (BN) at the other ear as shown. Further, for the masked threshold determinations ($N_{u,25}S_{bc}$) the level of the masking noise was varied in 10-dB steps for the Conventional Receivers, Table IV, and 5- or 10-dB steps for the Pedersen Receivers, Table V. It should be noted that the spectrum level of the blocking noise was always 25 dB higher than that of the masking noise. When the signals were presented by air conduction, the quiet thresholds (QAT's) were obtained for each ear with no noise. Finally, for the masked threshold determinations (N_mS_m) the masking noise was varied in 20-dB steps for the Conventional Receivers, Table IV, and 10- or 20-dB steps for the Pedersen Receivers, Table V.

The order of units and the order of signal pathways (bone or air conduction) were separately randomized. For both bone- and air-conducted signals the quiet threshold determinations always preceded those for the masked threshold conditions $N_{u,25}S_{bc}$ or N_mS_m. For each of the conditions the order in which the levels of the masking noise were presented was randomized.

An example of the sequence of threshold determinations for a typical block follows. The unit began with the determination of quiet absolute thresholds by bone conduction for each ear. Then eight thresholds were determined for the bone-conduction condition; two for each of the four levels of the masking noise. The noises were then turned off and the experimenter removed the bone-conduction transducer from the subject's head, but left the receivers in place. The determinations of the quiet thresholds for air conducted signals were then obtained for each ear. Finally, four masked thresholds were determined for the air-conducted signal; two for each of the two levels of the masking noise. Each subject completed one unit of a block during an experimental sitting.

RESULTS

The results of this experiment are shown in the eight panels of Fig. 9. The abscissae for each of the eight panels are the spectrum levels (re 0.0002 μbar) of the masking noise. The ordinates on the left of each panel are sound pressure levels (SPL's), while those on the right are RMS velocities expressed in decibels re 1.0 cm/sec. The test signals are ordered in frequency (250, 500, 1000, and 2000 cps) from the top to the bottom panels. The panels on the left show the data obtained

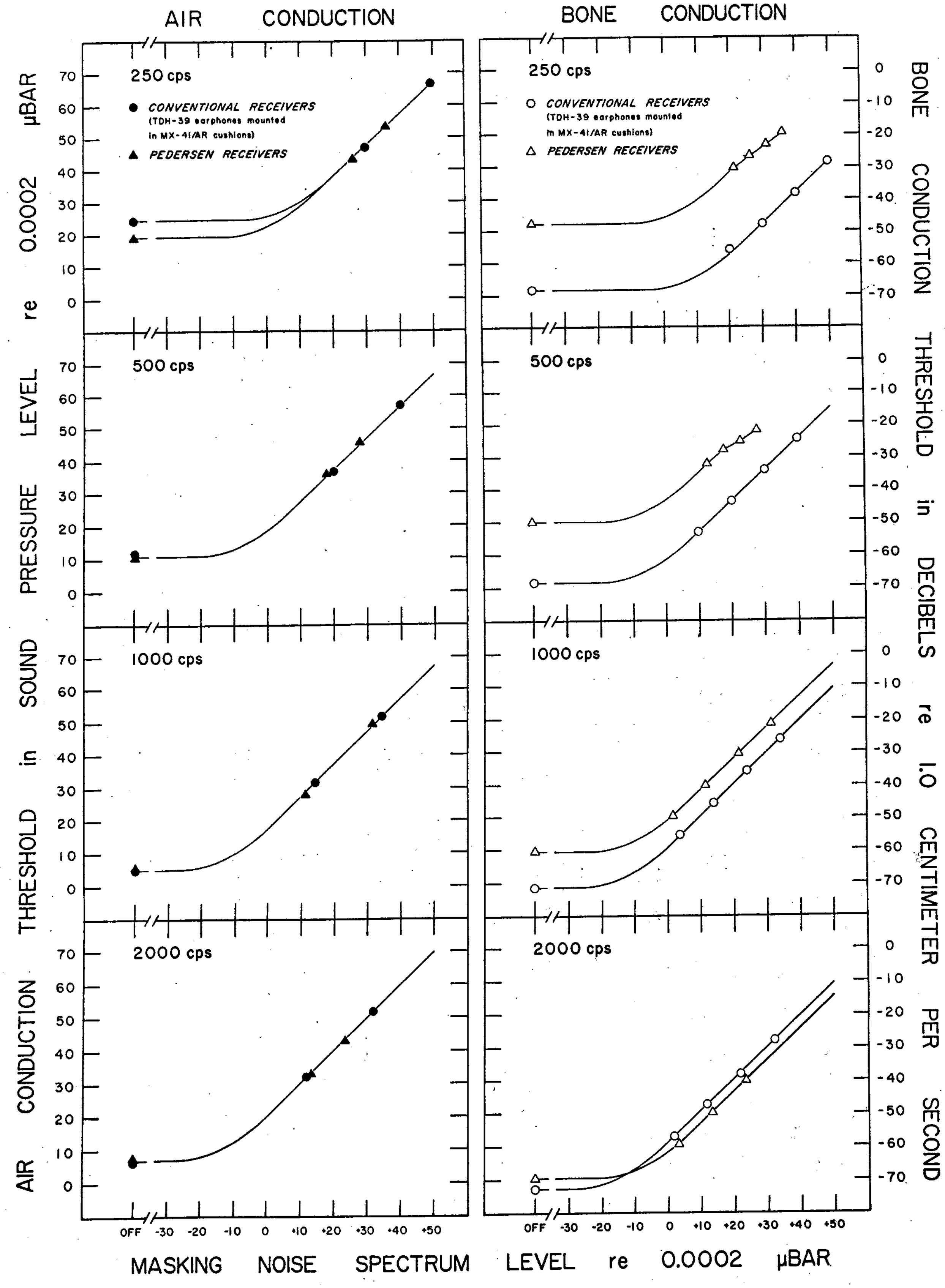

Fig. 9. The results of Experiment III. The masking functions are shown for both air and bone conduction as obtained for the Conventional and Pedersen Receivers. See text for a complete description.

for air conduction, while the panels on the right show the data obtained for bone conduction.

The bone-conduction thresholds are represented by the open circles for the Conventional Receivers (TDH-39 earphones mounted in MX-41/AR cushions) and by the open triangles for the Pedersen Receivers; these values are to be read from the vertical axis on the right of each panel. The air-conduction thresholds are represented by the filled circles for the Conventional Receivers and by the filled triangles for the Pedersen Receivers; these values are to be read from the vertical axis on the left of each panel. On each panel the point above the abscissa marked 'OFF' is a quiet absolute threshold.

The results shown in Fig. 9 are the basic data of the experiment and they are given in numerical form in Table VII. Each masked threshold represents the mean of 40 determinations, while each quiet threshold represents the mean of 20 determinations.

The data of Fig. 9 are replotted in Figs. 10 and 11. For Figs. 10 and 11 the abscissae for the four panels are the levels per cycle of the masking noises expressed relative to the quiet absolute threshold for each of the signal frequencies. The ordinates for the panels are sensation levels (SL's) for

Table VII. Data of Experiment III. Quiet (noise OFF) and masked thresholds are shown as a function of signal frequency for the Conventional and Pedersen Receivers. Air-conduction thresholds are in sound pressure level (SPL) re 0.0002 μbar, while bone-conduction thresholds are in terms of velocity expressed in decibels (dB) re 1.0 cm/sec (RMS).

	CONVENTIONAL RECEIVERS			PEDERSEN RECEIVERS		
Frequency cps	Masking Noise Spectrum Level	Bone Conduction dB re 1 cm/sec	Air Conduction SPL	Masking Noise Spectrum Level	Bone Conduction dB re 1 cm/sec	Air Conduction SPL
	OFF	-68.4	+24.6	OFF	-47.6	+19.0
	+19.7	-55.8	-	+21.1	-30.4	-
250	+29.7	-47.8	+46.8	+26.1	-26.9	+43.1
	+39.7	-38.1	-	+31.1	-23.1	-
	+49.7	-28.2	+66.6	+36.1	-19.4	+53.3
	OFF	-68.4	+12.0	OFF	-50.0	+10.6
	+ 9.7	-53.0	-	+12.9	-32.2	-
500	+19.7	-44.1	+36.9	+17.9	-27.8	+35.7
	+29.7	-34.1	-	+22.9	-25.2	-
	+39.7	-24.3	+57.2	+27.9	-21.9	+45.3
	OFF	-71.5	+ 4.9	OFF	-60.7	+ 5.8
	+ 3.9	-55.4	-	+ 1.2	-49.8	-
1000	+13.9	-45.6	+31.7	+11.2	-40.8	+27.9
	+23.9	-36.0	-	+21.2	-31.0	-
	+33.9	-26.2	+51.7	+31.2	-21.8	+49.1
	OFF	-72.7	+ 6.0	OFF	-69.8	+ 7.9
	+ 1.8	-56.9	-	+ 3.3	-59.3	-
2000	+11.8	-47.1	+32.0	+13.3	-49.9	+33.1
	+21.8	-38.0	-	+23.3	-40.1	+43.4
	+31.8	-27.5	+52.0	-	-	-

Fig. 10 and relative decibels for Fig. 11. The thresholds shown in Fig. 10 are sensation levels, while for Fig. 11 the masking functions are adjusted to coincide at masked threshold rather than at quiet threshold as is the case for Fig. 10. The key which matches the data points to the experimental conditions is the same as in Fig. 9.

DISCUSSION

Masking Functions.

The monaural masked threshold is related to the noise level by the data given in Table VII and shown in Fig. 9. The curves shown in Fig. 9 are called masking functions.

The data for the thresholds for the air-conducted signals were obtained in the quiet and at two levels of the masking noise. Only these few points were needed because the masking functions for air conduction are well established in the literature[19]. On the other hand, four masked and a quiet threshold were used for the bone-conducted signals since these were essentially 'new' experiments.

As it turned out fourteen of the sixteen functions shown in Fig. 9 were fitted to the data by means of a 'template curve' derived from the masking function for air conduction reported by Hawkins and Stevens[19]. In most cases the shapes of the masking functions for the bone-conducted signals are clearly identical to those for air-conducted signals; only those bone-conduction functions for the Pedersen Receivers when the signal was 250 or 500 cps differ from the others.

Figure 10 shows similarities and differences between the shapes of the masking functions for the various conditions of this experiment more clearly than Fig. 9. For Fig. 10 the thresholds are in sensation level and the air-conducted masking noise is in level per cycle expressed relative to the quiet absolute threshold for the appropriate air-conducted signal. In the units of Fig. 10 at any one frequency the masking functions are identical for all experimental conditions except those discussed below.

The bone-conduction masking functions for the Pedersen Receivers show two deviant effects. One effect, described previously, is the apparent non-linear relation between the signal threshold and the level of the masking noise for frequencies of 250 and 500 cps. A possible basis for this effect will be discussed in the section on the o c c l u s i o n e f f e c t . The other effect is clearly seen for the signal

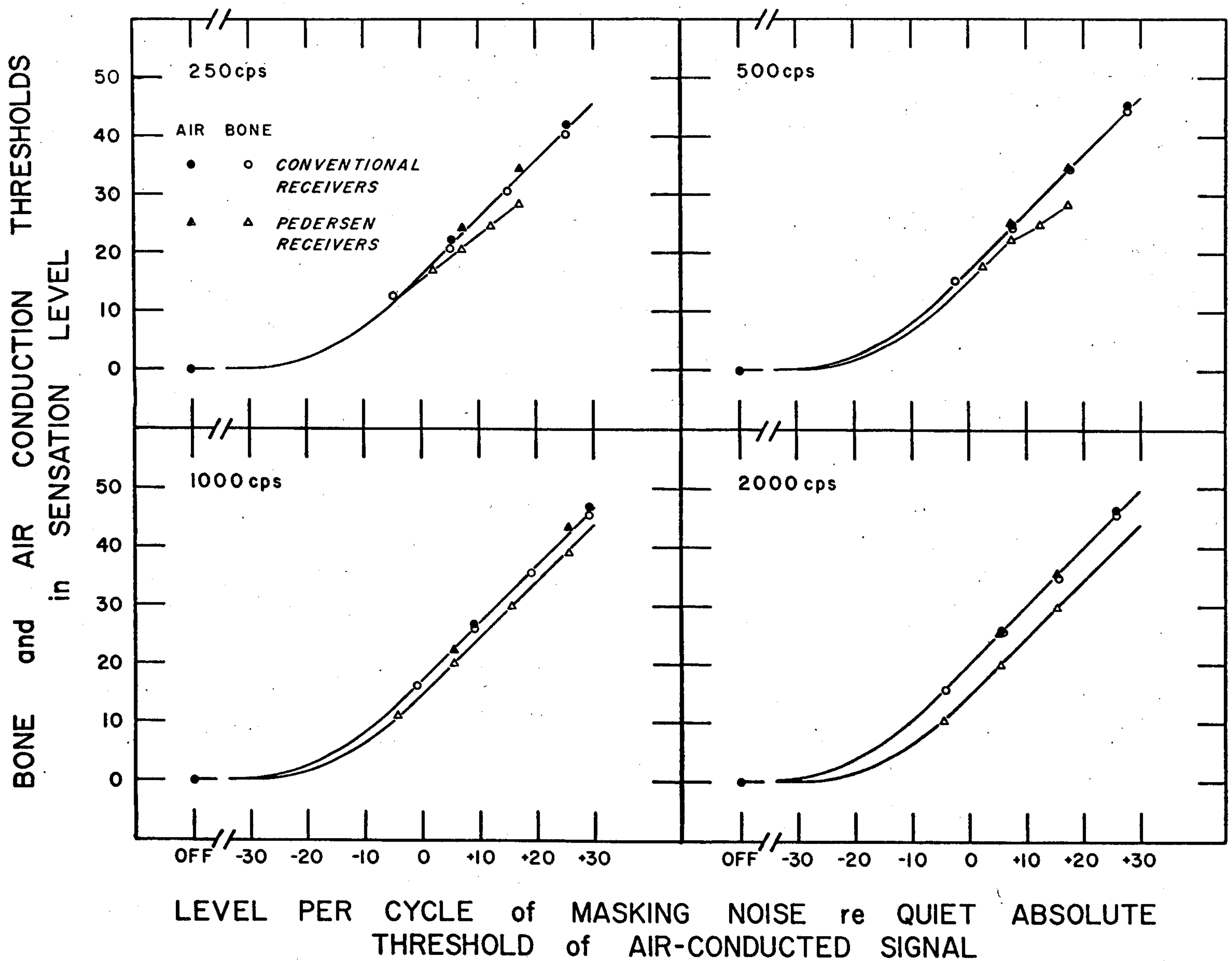

Fig. 10. The data of Fig. 9 replotted in sensation levels with the levels per cycle of the masking noise expressed relative to the quiet absolute thresholds of the test signals indicated in each panel.

frequency of 2000 cps. Although the shape of this masking function is identical to the others, it appears that for the same spectrum level of the masking noise there is less masking for the bone-conducted signal when the Pedersen Receivers are used than there is for the bone-conducted signal when the Conventional Receivers are used and for the air-conducted signals. A possible basis for this effect comes to light when the data of Fig. 10 are replotted in Fig. 11.

For Fig. 11 the masking functions are adjusted to coincide at masked threshold. When this method is used to display the data the quiet bone-conduction threshold at 2000 cps obtained when the Pedersen Receivers are over the ears appears to be deviant. The fact that this kind of discrepancy is unique to the Pedersen Receivers at only one frequency suggests that this discrepancy may be related to the quiet rather than the masked threshold determinations as might be inferred from Figs. 9 and 10. Indeed, the quiet threshold determinations become suspect when the level of the blocking noise used during the determinations of the quiet thresholds is considered. Tables IV and V show that the spectrum level of the blocking noise for the Pedersen Receivers was

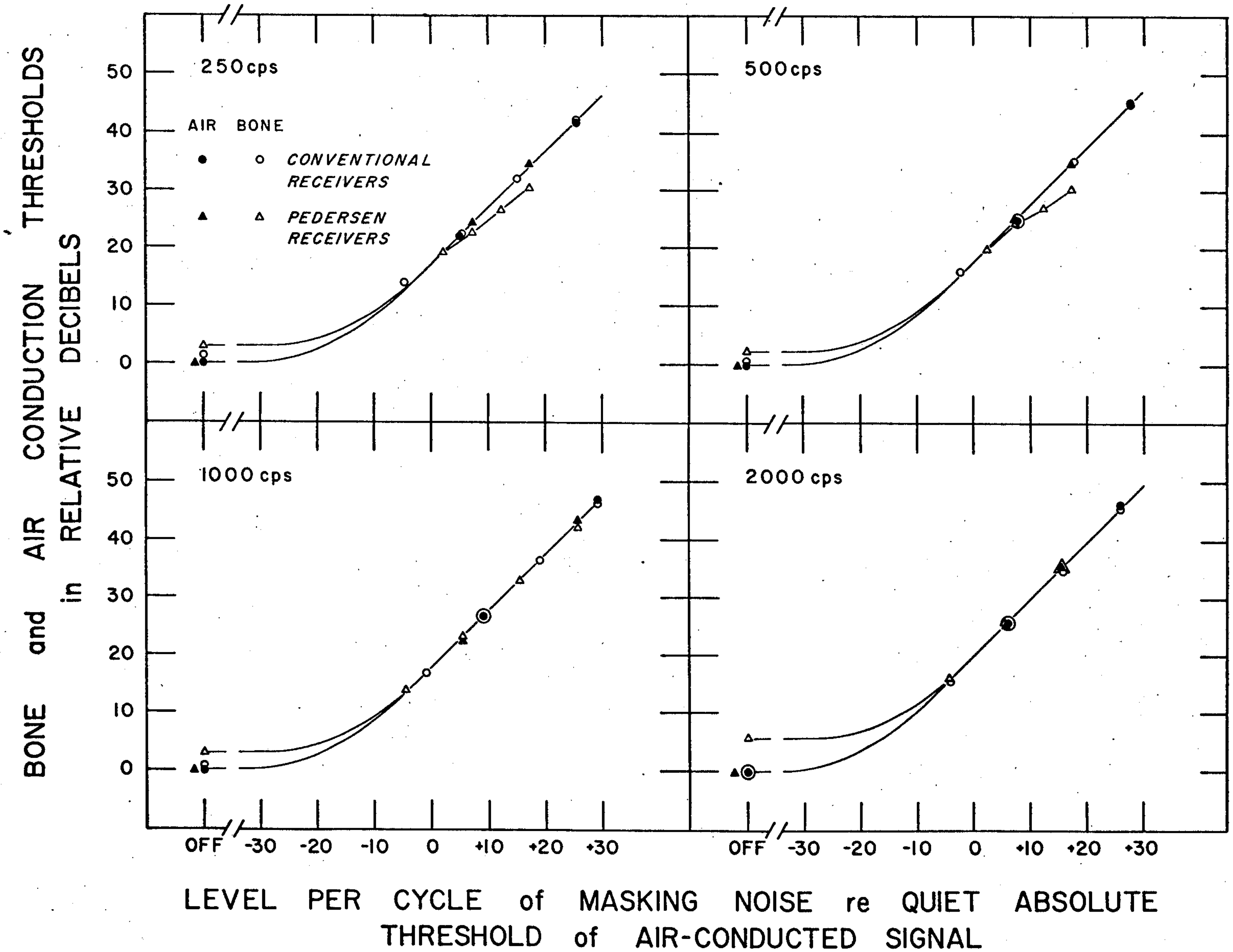

Fig. 11. The data of Fig. 9 replotted so that the masking functions coincide at masked threshold. The levels per cycle of the masking noise are expressed relative to the quiet absolute thresholds of the test signals indicated in each panel.

22 dB higher than that for the Conventional Receivers. The excessively high spectrum level for the Pedersen Receivers was, unfortunately, not noticed until Experiment III was completed. Although empirical evidence was not obtained, it may be that this noise was of sufficient level to produce either cross masking, central masking, or both of the bone-conducted signal at the other ear.

The Determination of Masking.

The masking functions for bone conduction shown in Fig. 9 can be used to determine the amount of noise required to produce a specific amount of masking of a bone-conducted signal at one ear. When the data in Fig. 9 are used for these determinations the results are only correct for the air- and bone-conduction transducer configurations used in this experiment. However, it is almost certain that similar data and masking functions could be obtained for other transducer configurations.

The masking functions in the present experiment are for two limiting cases: the case of a sizable occlusion effect (the Conventional Receivers); and the case of little or no occlusion effect (the Pedersen Receivers). Thus, similar functions could be interpolated between these two extremes for receivers that produce intermediate amounts of the occlusion effect.

An example of the determination of masking follows. Assume that 30 dB of masking is required, the signal frequency is 500 cps, and the Conventional Receivers are used. From column three of Table VII or from Fig. 9 the bone-conduction threshold is -38.4 dB re 1.0 cm/sec, that is, the quiet threshold (noise OFF) plus the amount of masking. In the appropriate panel of Fig. 9 locate this value on the ordinate and extend a horizontal line until it intersects the masking function. Now extend a line down from this intersection to the abscissa. The spectrum level of the masking noise as indicated on the abscissa is +24.5 dB. If the noise to be used has a flat spectrum and a bandwidth of 7000 cps, for example, then the overall SPL for the noise is +63 dB.

In conclusion, it should be noted that the method described in this experiment for obtaining monaural thresholds of bone-conducted signals provides a d i r e c t means for the determination of masking of this signal. Although the masking functions shown in Fig. 9 are predictable from those for air-conducted signals, as was generally supported by the results, the literature provided no direct information concerning such conclusions. Considerable information, however, is available for the two limiting cases of either too much masking or too little masking of bone-conducted signals. That is to say, the present experiment measures directly the amount of masking of a bone-conducted signal produced by an air-conducted noise when both signal and noise are at the same ear. Previous experiments have been designed to show whether too little or too much noise when applied to one ear in order to successfully mask the signal in that ear influenced the measurement of threshold at the other ear. See for example Studebaker[30] or Konig[24]. As a result the masking of the signal between these two limits can only be indirectly infered. Thus, this experiment provides a direct means for investigating the actual effect of masking of a bone-conducted signal at one ear.

Physical Measures of the Threshold Signal.

As previously noted this experiment provided for the calibration in physical units of both air- and bone-conduction transducers. Thus, physical measures were calculated for both air- and bone-conducted signals when they were set to threshold intensity. In Fig. 9 and Table VII the threshold intensities for air conduction are in sound pressure levels (SPL's) re 0.0002 μbar, while for bone conduction they are in decibels re 1.0 cm/sec (RMS). Although such physical measurements for air conduction are commonplace, they are seldom encountered for bone conduction. The apparatus and calibration procedures for both air- and bone-conduction measurements were described in Chapter II.

As was previously noted in Chapter I, stimulation in the inner ear is identical for both air- and bone-conduction pathways.[2, 4, 25, 33] Therefore, for a particular experimental condition in this experiment (frequency, receiver, and kind of threshold) the physical measure for the bone-conducted signal has an equivalent physical measure for the air-conducted signal when each signal is set to its respective threshold. Values for these equivalencies are, in fact, the data given in Table VII.

Table VIII shows more directly the equivalence between the physical measures for air- and bone-conducted signals for the several conditions of this experiment. The values given in Table VIII were computed from the data given in

Table VIII. Sound pressure levels in decibels (re 0.0002 μbar) for air-conducted signals that are equivalent to bone-conducted signals generated when the velocity at the driver tip is 1.0 cm/sec (RMS). The equivalency was determined at either masked or quiet threshold and extrapolated, decibel for decibel, to the reference velocity of 1.0 cm/sec (RMS).

FREQUENCY cps	Conventional Receivers Quiet SPL	Conventional Receivers Masked SPL	Pedersen Receivers Quiet SPL	Pedersen Receivers Masked SPL
250	93.0	94.7	66.6	68.5(?)[a]
500	80.4	81.3	60.6	63.0(?)
1000	76.4	77.6	66.5	69.4
2000	78.7	79.3	77.7	83.3[b]

[a]The values for 250 and 500 cps were calculated from points believed to be on the linear portion of the masking function curves shown in Fig. 9.

[b]See the section on Masking Functions for a discussion of this deviant effect at 2000 cps for the Pedersen Receivers.

Table VII according to the formula x dB SPL ≅ y dB velocity, where x is the sound pressure level (SPL) in decibels (re 0.0002 μbar) for the air-conducted signal and y is the velocity in decibels (re 1.0 cm/sec (RMS)) of the driver tip of the bone-conduction transducer for the bone-conducted signal. For this table y is equal to 1.0 cm/sec (RMS) and the values for x are given according to frequency for the experimental conditions.

In order to show that the physical measurements for bone conduction are reasonable, the data for the quiet absolute thresholds with the Pedersen or Conventional Receivers over the ears are shown in Fig. 12 along with data reported by Corliss, Smith, and Magruder.[10] For Fig. 12 the abscissae are the signal frequencies, while the ordinates are decibels re 1.0 cm/sec (RMS). The open triangles and circles represent the quiet thresholds for the Pedersen and Conventional Receivers, respectively, while the x's represent the quiet thresholds reported by Corliss et al. Their data are for binaural thresholds with the ears unoccluded, while the data for the present experiment is for monaural thresholds with the ears occluded.

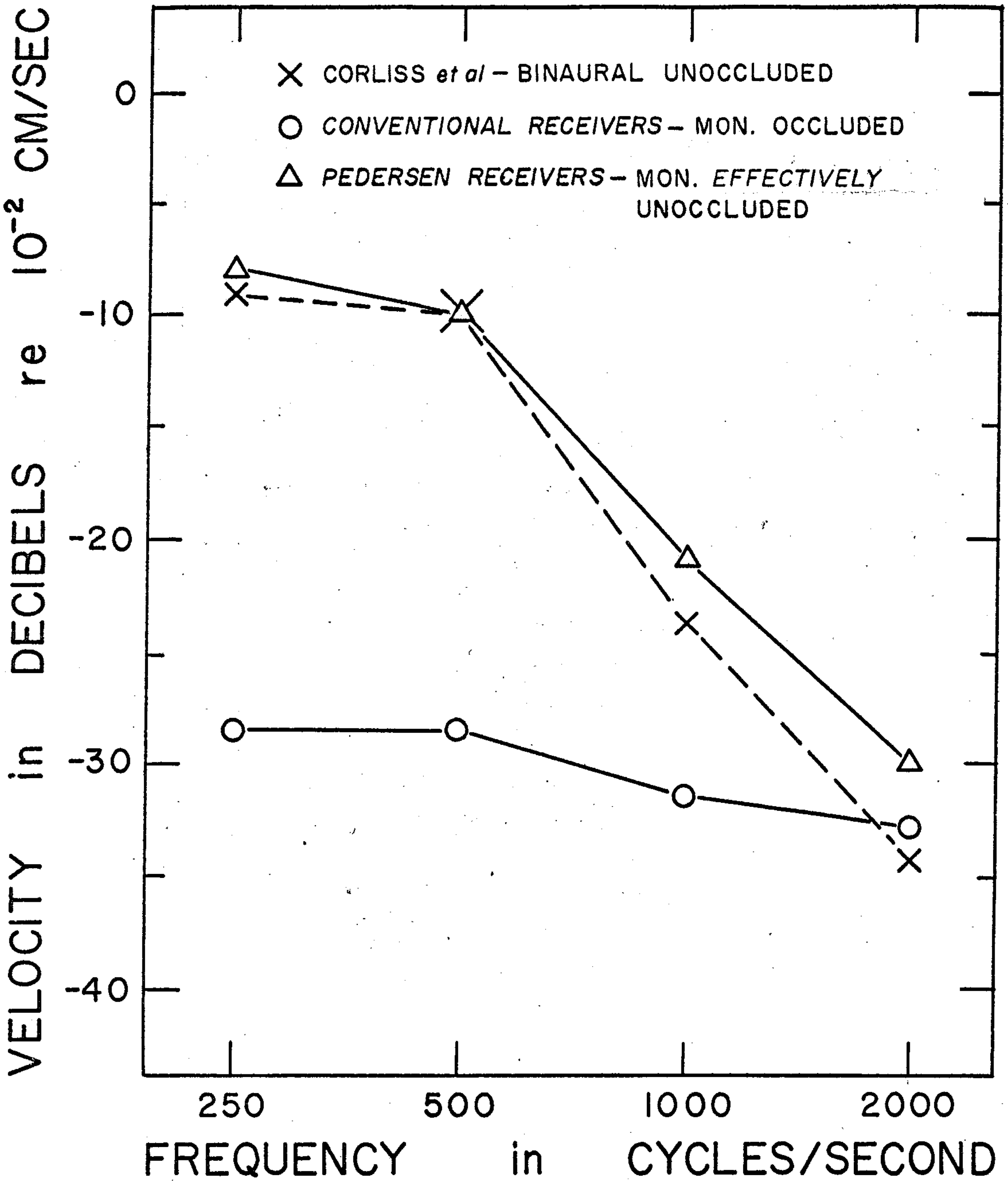

Fig. 12. Quiet absolute thresholds for bone conduction obtained for the Conventional and Pedersen Receivers. Data reported by Corliss et al are also shown.

However, Elpern and Naunton[14] have reported that the Pedersen Receivers have little or no effect on the bone-conduction threshold. Thus, the present data can be considered as representing monaural thresholds with the Pedersen Receivers, although occluding the ears, producing little or no 'occlusion effect'.

The agreement between the data for the Pedersen Receivers and that of Corliss et al shown in Fig. 12 is good. The differences between these two sets of data that do appear (about 3 dB) may be due to the differences between monaural and binaural thresholds. On the other hand, these differences are more likely the result of different measurement systems and techniques being used. It should be noted that the agreement between these data also suggests that the Pedersen Receivers, in fact, have no effect on the bone-conduction threshold and this observation supports the conclusions of Elpern and Naunton mentioned above.

On the other hand the data shown in Fig. 12 for the Conventional Receivers indicates the lowering of threshold due to the occlusion effect. Moreover, these thresholds are nearly independent of frequency. The agreement between all three sets of data for a frequency of 2000 cps was predicted because the occlusion effect is generally reported to be negligible for this frequency.

In addition the good agreement between the results for the Pedersen Receivers and those of Coreliss et al for quiet thresholds lends support by extrapolation to the physical measurements of the bone-conducted signals at masked threshold.

In order to show that the physical measurements for air conduction are reasonable, the data for the quiet absolute thresholds obtained with the Conventional and the Pedersen Receivers are shown in Fig. 13 along with data for the proposed ISO* standard for quiet absolute threshold.[13] For Fig. 13 the abscissae are the signal frequencies, while the ordinates are sound pressure levels. The quiet thresholds are represented by the closed circles for the Conventional Receivers and the closed triangles for the Pedersen Receivers, while the <u>x</u>'s represent the thresholds for the proposed ISO standard.

The agreement between threshold measurements for this experiment and the proposed ISO standard is good. Therefore, this good agreement for quiet thresholds also lends support, by extrapolation, to the physical measurements of the air-conducted signals at masked threshold.

Linearity of the Bone-conduction Transducer

Psychophysical measures were obtained of the output of the bone-conduction transducer as a function of input. These measures are shown in Fig. 9 as the masking functions for bone conduction. The fact that

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* ISO stands for the International Organization for Standardization.

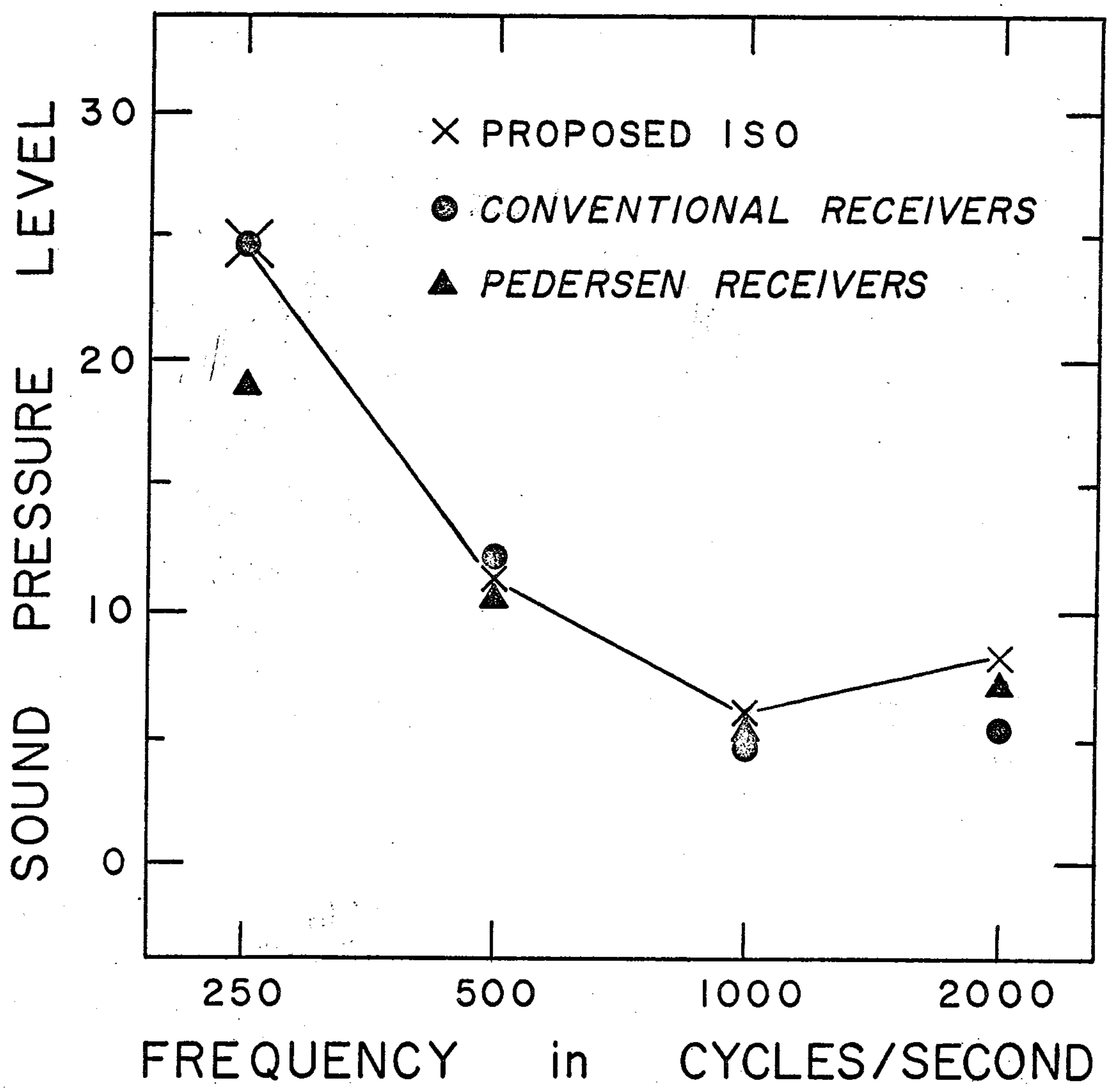

Fig. 13. Quiet absolute thresholds for air conduction for the Conventional and Pedersen Receivers. The proposed ISO thresholds are also shown.

most of these functions are linear as had been predicted, suggests that the transducer itself is operating within its linear range. What appears to be a non-linear effect for 250 and 500 cps with the Pedersen Receivers is not traceable to the transducer. This effect and reasons for it are discussed in the next section.

With the knowledge that most of the masking functions for bone conduction are linear, that is a 10-dB increase in the level of the noise requires a 10-dB increase in the level of the signal to maintain threshold, the method provides a means for the calibration of bone-conduction transducers at input levels greater than those required for the quiet threshold. Thus, the generation of masking functions for bone conduction could be used to indicate any abnormal effects due to the transducer itself.

The Occlusion Effect

The experiment was designed to assess the 'occlusion effect' on the masked as well as the quiet threshold of bone-conducted signals. The occlusion effect is the lowering of bone-conduction thresholds at low frequencies when the external ears are occluded. Different degrees of occlusion were provided, in this experiment, by two kinds of earphones, or receivers. The Conventional Receivers (TDH-39 dynamic earphones mounted in MX-41/AR cushions) occlude with only a small volume and produce a sizable occlusion effect, while the Pedersen Receivers, with a large volume, are reported to produce little or no occlusion effect.[14]

The magnitude of the occlusion effect in the bone-conduction thresholds for the Pedersen and the Conventional Receivers can be determined from the data in Table VII and from Fig. 9. The difference in thresholds between the two types of receivers is nearly the same at masked as it is at quiet threshold. The mean difference in thresholds for a 250-cps signal is about 22 dB, while for a 500-cps signal it is 18 dB. The occlusion effect for a 1000-cps signal is about 10 dB, while for a 2000-cps signal it is very small, with an indicated value of ±5 dB.

The fact that the Pedersen Receivers produce little or no occlusion effect (as mentioned previously) is important and it is the basis for a possible explaination of certain unanticipated results obtained for these receivers. Figure 9 indicates for these receivers that the shapes of the masking functions for air- and bone-conducted signals are not identical when the signal was 250 or 500 cps. In addition, these results may also relate to certain observations made by the subjects.

All the subjects made the following observations. They reported varying degrees of difficulty in determining the masked thresholds for bone conduction when the signal was 250 or 500 cps but only when the Pedersen Receivers and not when the Conventional Receivers were used. The comments were that it was difficult to differentiate between 'f e e l i n g' and 'h e a r i n g' the signal when it was set to threshold intensity. It is not known how to interpret these comments and they are simply reported here.

The deviant thresholds at 250 and 500 cps may be related to the activation of the intra-aural muscles, or, in more general terms, the acoustic reflex. Before proceeding directly to the possible role of the acoustic reflex in explaining the results obtained, the following factors must be considered.

For the case of the Conventional Receivers, which produce a sizable occlusion effect, the bone-conduction threshold at low frequencies is controlled by an air-conducted component of the bone-conducted signal. At the present time it is not known exactly how this air-conducted component is generated in the occluded external auditory meatus. However, it has been suggested by some investigators[2,4] that sound is generated by the deformation of the meatus walls, while others[1] support the notion that an increase in the impedance of the middle ear causes a decrease in energy loss from the inner ear via the ossicular chain.

Regardless of how this air-conducted component is generated within the occluded meatus, it is important to note its existence and that for the Conventional Receivers the level of the air-conducted component is high and controls the bone-conduction threshold. Because of this effect the normal bone-conduction pathway is 'by-passed' and has little influence on the air-conducted component generated in the meatus. In contrast, for the Pedersen Receivers the level of the air-conducted component is very low or nearly non-existent and the bone-conducted signal itself controls the threshold.

Now in terms of the air-conduction pathways the following situations exist. For the Conventional Receivers, the large air-conducted component of the bone-conducted signal generated within the meatus and the masking noise are both present at one ear, while the blocking noise is at the other ear. In contrast, for the Pedersen Receivers the signal is transmitted via the bone-conduction pathway and only the masking and blocking noises are carried by air conduction.

Now the possible role of the acoustic reflex can be considered. If the acoustic reflex were indeed activated, then the resulting attenuation would diminish the air-conduction signals and noises together. Thus, in the case of the Conventional Receivers, where the bone-conducted signal is, in fact, primarily an 'air-conducted' signal, the masking functions for 250- and 500-cps signals would show no differential effect due to this attenuation introduced by the acoustic reflex. In contrast, in the case of the Pedersen Receivers it is hypothesized that the air-conducted masking noise would be attenuated <u>more</u> than the bone-conducted signal thereby resulting in <u>less</u> masking. It is this differential effect between the air- and bone-conduction pathways which probably accounts for the deviant masking functions.

If activation of the acoustic reflex occurs, the blocking noise must be considered as the activating source. Consider now the levels of the blocking noise when the highest two levels of the masking noise were used. The overall sound pressure levels for the blocking noises are simply the spectrum levels of the masking noises(as shown in Table VII) plus the bandwidth for the noise (700 cps or 28.5 dB) plus 25 dB (the difference between the two noises). Thus, the overall sound pressure levels of the blocking noises for the Conventional Receivers were 103.5 and 93.5 dB, while for the Pedersen Receivers they were 90.5 and 81.5 dB when the signals were 250 and 500 cps, respectively. For these levels of the blocking noise it was possible to measure the acoustic reflex for both types of receivers by means of an electro-acoustic impedance measureing system.* The amount of attenuation resulting from the acoustic reflex is not known nor was any attempt made to measure the shifts in threshold that might occur by means of other psychophysical procedures.

In conclusion, it is hypothesized that, with the activation of the acoustic reflex and the resultant attenuation, though small, in the air-conduction pathway, for the Conventional Receivers the noises and the air-conducted component of the bone-conducted signal are attenuated together with no differential effect on the masking function. In contrast,

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*First the static acoustic impedance was measured at a plane within the right external auditory meatus on one subject. Then the blocking noise was presented to the left ear and the change in the magnitude of the acoustic impedance was measured. These measurements were carried out by Dr. David J. Lilly.

in the case of the Pedersen Receivers only the masking noise is attenuated and the masking functions show the differential effect between the signal pathway (bone conduction) and the noise pathway (air conduction).

Variability of the Threshold Signal

A summary table of standard deviations (root mean variances) of the threshold signals are shown in Table IX. Table IX* gives the root mean variances in decibels for quiet and masked thresholds for signals presented either by bone or air conduction with either the Conventional or the Pedersen Receivers over the ears.

The first and second lines in Table IX are the root mean variances ($\sigma_{W_{LCR}}$) and the standard error of the means ($\sigma_{\overline{W_{LCR}}}$) based on two thresholds. These standard deviations are taken for a given listener, condition, and replication, that is, for measures within listeners, conditions, and replications. The root mean variances for measures within listeners and conditions but between replications ($\sigma_{W_{LC}B_R}$) are given in the third line, while the root mean variances for measures within conditions and replications but between listeners ($\sigma_{W_{CR}B_L}$) are given in the fourth line of this table.

The following generalities can be made from Table IX: The standard error of the means for measures within listeners, conditions, and

*Complete tables of the mean variances (Table X) and the root mean variances (Table XI) can be found in Appendix A.

Table VIII. Summary table of root mean variances of threshold signal in decibels.

	BONE CONDUCTION				AIR CONDUCTION			
	Conventional		Pedersen		Conventional		Pedersen	
	Quiet	Masked	Quiet	Masked	Quiet	Masked	Quiet	Masked
$\sigma_{W_{LCR}}$	-	1.220	-	1.313	-	1.195	-	1.242
$\sigma_{W_{\overline{LCR}}}$	-	0.863	-	0.928	-	0.845	-	0.881
$\sigma_{W_{LC}B_R}$	2.675	2.532	2.708	2.276	1.922	1.323	1.587	1.216
$\sigma_{W_{CR}B_L}$	4.860	6.181	5.709	5.459	3.234	1.608	3.286	1.702

replications ($\sigma_{W_{\overline{LCR}}}$) is small (less than 1 dB) and nearly the same for masked thresholds when the signal is either by air or bone conduction and when either the Conventional or Pedersen Receivers are used. Thus, the variability in threshold determinations is small provided the receivers and bone-conduction transducer are not removed between threshold determinations.

The variability for measures within listeners and conditions but between replications is larger for bone- and air-conducted signals than it is within listeners, conditions, and replications. The root mean variances between replications ($\sigma_{W_{LC}B_R}$) are larger than the standard errors of the means within replications ($\sigma_{W_{\overline{LCR}}}$)* by about 1.5 dB for bone conduction and about 0.5 dB for air conduction.

Notice also that for the case of bone-conducted signals the root mean variances between replications ($\sigma_{W_{LC}B_R}$) appear to be about the same for all four of the conditions shown in Table VIII, while for the case of air-conducted signals the root mean variances are slightly larger for quiet thresholds than those for masked thresholds for both types of receivers.

Notice, however, that the root mean variances for between replications ($\sigma_{W_{LC}B_R}$) are larger for bone-than for air-conducted signals. This suggests

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*These standard deviations are comparable for masked thresholds since the thresholds used in calculating the between-replications standard deviations were each the means of two thresholds obtained within a replication.

that the placement of the bone-conduction transducer on the head is more critical than is the placement of the air-conduction receiver over the ears.

The root mean variances for measures within conditions and replications but between listeners ($\sigma_{W_{CR}B_L}$) are still larger than those discussed above. For bone conduction they are about 2 to 3 dB greater than those measures between replications ($\sigma_{W_{LC}B_R}$) and they appear to be nearly the same for quiet and masked threshold and for the Conventional and Pedersen Receivers. For air conduction the variability among listeners at masked threshold is only slightly greater than the variability between replications, while for quiet thresholds the variability among listeners is clearly larger than that between replications.

Finally, referring to Table XI in Appendix A, the variability between listeners ($\sigma_{W_{CR}B_L}$) for bone conduction is greater for signal frequencies of 1000 and 2000 cps than it is for those of 250 and 500 cps.

CONCLUSIONS

The conclusions for this experiment as well as those for the other two experiments are given in the next chapter, Chapter VI.

CHAPTER VI

SUMMARY and CONCLUSIONS

The primary purpose of this study was to develop and evaluate a method for obtaining monaural thresholds for bone-conducted signals (tones) masked by air-conducted noises. The method required air-conducted noise (masking noise) at the ear at which bone-conduction thresholds were determined and another air-conducted noise (blocking noise) at the other ear. The blocking noise was used to functionally eliminate one ear from the experiment. The evaluation of this method indicated that the blocking noise must be both independent of and about 25 dB higher in level than that of the masking noise. These conclusions resulted from Experiment I for the case of bone-conducted signals and air-conducted noises and from Experiment II for the case of signals and noises by air conduction. Both of these experiments in turn supported the results of Weston and Miller[32] for the case of signals and noises by air conduction at a signal frequency of 500 cps.

Experiment III provided several kinds of information:

Masking Functions. The shapes of the curves relating monaural masked thresholdsto noise level were identical for air- and bone-conducted signals except when the Pedersen Receivers (large volume) were over the ears and when the bone-conducted signal was 250 and 500 cps. The deviant masking functions are probaly due to the action of the acoustic reflex. This seems reasonable since, (1) blocking noise at these levels produced a change in the acoustic impedance at the eardrum and thus an acoustic reflex action, and (2) when the Pedersen Receivers were over the ears, the paths for bone-conducted and air-conducted sounds were probably differentially affected by the action of the acoustic reflex.

The Determination of Masking. The amount of air-conducted noise required to produce a specific amount of masking of a bone-conducted signal at an ear can be determined from the data. These determinations can be made for two limiting cases; that of a sizable occlusion effect (TDH-39 earphone mounted in a MX-41/AR cushion) and that of no occlusion effect (Pedersen Receivers). Determinations for other earphone-cushion volumes can be interpolated.

Physical Measures of the Threshold Signal. Physical measures were calculated for both air- and bone-conducted signals at threshold intensity. For air-conducted signals they were calculated in terms of coupler-calibration measurements, while for bone-conducted signals a velocity-sensitive measurement system attached to the bone-conduction transducer was used. This latter system was calibrated by means of an independent source (other than the transducer) and also by means of comparison calibrations with another, highly accurate, velocity-sensitive measurement system with the bone-conduction transducer as the source. The quiet thresholds for both air- and bone-conducted signals were in good agreement with similar data reported in the literature.

Linearity of the Bone-Conduction Transducer. The fact that most of the masking functions were found to be linear with slope one means that the method, under certain conditions, provides a means for the calibration of bone-conduction transducers at input levels greater than those required at quiet threshold.

The Occlusion Effect. The 'occlusion effect' is maintained at masked as well as quiet threshold. The magnitudes of the occlusion effect for the Conventional Receivers (TDH-39 earphones mounted in MX-41/AR cushions) compared to the Pedersen Receivers (large volume) were about 22, 18, 10, and ±3 dB for frequencies of 250, 500, 1000, and 2000 cps, respectively.

Variability of the Threshold Signal. The within-listener variability of the signal threshold was small for masked threshold determinations of air- and bone-conducted signals and also for the Conventional and Pedersen Receivers. The standard errors of means based on two thresholds were less than 1 dB. The variability for measures within listeners and conditions but between replications was larger than the within-listener variability. For air conduction the quiet thresholds showed a slightly larger variability than for masked threshold, while for bone conduction the variability for both quiet and masked threshold is about the same. The variability across replications is larger for bone- than for air-conducted signals. The variability for measures within conditions and replications but between listeners was still larger than those reported above; there was less variability for masked than for quiet thresholds by air conduction, while for bone conduction the variability seemed to be independent of the kind of threshold or receiver used. It appears that for bone-conducted signals the masked and quiet thresholds show about the same degree of variability, while for air-conducted signals the masked threshold shows less variability than the quiet threshold.

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APPENDIX

Table of Mean Variances

Table of Root Mean Variances

TABLE X

Mean variances for measures within listeners, conditions, and replications ($\sigma^2_{W_{LCR}}$).

Frequency cps	BONE CONDUCTION Conventional Quiet	Conventional Masked	Pedersen Quiet	Pedersen Masked	AIR CONDUCTION Conventional Quiet	Conventional Masked	Pedersen Quiet	Pedersen Masked
250	-	1.65	-	2.54	-	1.32	-	1.25
500	-	1.43	-	1.72	-	1.28	-	1.96
1000	-	1.56	-	1.44	-	1.36	-	1.99
2000	-	1.73	-	1.20	-	1.75	-	0.98
$\sum\sigma^2$	-	5.956	-	6.895	-	5.708	-	6.175
grand σ^2	-	1.489	-	1.723	-	1.427	-	1.544
grand $\bar{\sigma}^2$	-	0.745	-	0.862	-	0.714	-	0.777

Mean variances for measures within listeners and conditions but between replications ($\sigma^2_{W_{LC}B_R}$).

Frequency cps	BC Conv. Quiet	BC Conv. Masked	BC Ped. Quiet	BC Ped. Masked	AC Conv. Quiet	AC Conv. Masked	AC Ped. Quiet	AC Ped. Masked
250	7.150	7.562	3.925	2.112	3.000	1.347	1.625	1.512
500	7.425	5.478	8.775	5.949	5.150	1.756	1.200	1.816
1000	6.700	8.364	13.325	9.609	2.650	1.394	3.950	1.399
2000	7.350	4.248	3.300	3.058	3.975	2.500	3.300	1.191
grand σ^2	7.156	6.413	7.331	5.182	3.694	1.749	2.519	1.479

Mean variances for measures within conditions and replications but between listeners ($\sigma^2_{W_{CR}B_L}$).

Frequency cps	BC Conv. Quiet	BC Conv. Masked	BC Ped. Quiet	BC Ped. Masked	AC Conv. Quiet	AC Conv. Masked	AC Ped. Quiet	AC Ped. Masked
250	10.536	22.750	12.886	9.975	6.296	4.420	4.820	3.860
500	6.636	13.052	39.766	21.721	4.946	1.673	5.886	3.618
1000	56.330	34.322	59.933	44.698	7.020	1.900	12.696	1.870
2000	20.996	82.676	17.786	42.795	23.580	2.352	19.813	2.247
grand σ^2	23.624	38.200	32.592	29.795	10.460	2.586	10.800	2.898

TABLE XI

Root mean variances for measures within listeners, conditions, and replications ($\sigma_{W_{LCR}}$).

Frequency	BONE CONDUCTION				AIR CONDUCTION			
	Conventional		Pedersen		Conventional		Pedersen	
cps	Quiet	Masked	Quiet	Masked	Quiet	Masked	Quiet	Masked
250	-	1.285	-	1.594	-	1.149	-	1.118
500	-	1.196	-	1.311	-	1.131	-	1.400
1000	-	1.249	-	1.200	-	1.166	-	1.411
2000	-	1.315	-	1.095	-	1.323	-	0.989
grand σ	-	1.220	-	1.313	-	1.195	-	1.242
grand $\bar{\sigma}$	-	0.863	-	0.928	-	0.845	-	0.881

Root mean variances for measures within listeners and conditions but between replications ($\sigma_{W_{LC}B_R}$).

250	2.674	2.749	1.981	1.453	1.732	1.161	1.275	1.229
500	2.725	2.341	2.962	2.439	2.269	1.325	1.095	1.347
1000	2.588	2.892	3.650	3.099	1.628	1.181	1.987	1.183
2000	2.711	2.061	1.817	1.749	1.994	1.581	1.817	1.091
grand σ	2.675	2.532	2.708	2.276	1.922	1.323	1.587	1.216

Root mean variances for measures within conditions and replications but between listeners ($\sigma_{W_{CR}B_L}$).

250	3.246	4.769	3.589	3.158	2.509	2.102	2.195	1.965
500	2.576	3.613	6.306	4.661	2.224	1.292	2.426	1.902
1000	7.505	5.858	7.742	6.686	2.649	1.378	3.563	1.367
2000	4.582	9.093	4.217	6.542	4.856	1.534	4.451	1.499
grand σ	4.860	6.181	5.709	5.459	3.234	1.608	3.286	1.702